Chapter 4

Emissions of Black Carbon

4.1 Summary of Key Messages

- Emissions of BC from U.S. sources total about 0.64 million tons (580 Gg) in 2005, which represents about 8% of the global total. Mobile sources account for a little more than half (52%) of the domestic BC emissions. Approximately 93% of the mobile source total is from diesel sources. Open biomass burning is the next largest source in the United States, accounting for about 35% of the total. In general, BC is concentrated in urban areas, where populations are largest, making health an important issue in addition to climate in BC mitigation strategies.

- OC is a significant co-emitted pollutant among the major BC emitting sources. The United States is estimated to emit about 1.7 million tons (1500 Gg) of OC. The ratio and mass of BC and OC varies by source. Diesel combustion emissions produce the largest fraction of BC while emissions from open biomass burning are dominated by OC. More research is needed on how OC/BC ratios can be used to characterize the net climate impacts of different sources.

- Diesel sources have a low OC/BC ratio, making them strong candidates for mitigation. By 2030, domestic diesel emissions will be reduced by the phase-in of recent national mobile source emission standards, and other categories, such as open biomass burning, will emerge as top emitters of BC in the United States.

- More than two-thirds of the almost 8.4 million tons (7,600 Gg) of global BC emissions come from open biomass burning and residential sources. The regions of the world responsible for the majority (nearly 75%) of BC emissions world-wide are Africa, Asia, and Latin America. In developing countries, biomass burning and residential sources are the dominant sources of BC, while in developed countries, emissions of BC are lower and are often dominated by transportation and industry.

- Long-term historic trends of BC emissions in the United States reveal a dramatic increase in emissions from contained combustion sources from the mid-1880s to approximately the 1920s followed by a decline over the next eight decades. The decline can be attributed to changes in fuel use, more efficient combustion of coal, and implementation of PM controls. In contrast, developing countries (e.g., China and India) have shown a very sharp rise in BC emissions over the past 50 years.

- Characterization of domestic and global BC emissions and the subsequent development of BC emissions inventories are based on a limited number of existing source measurements. Better information is needed on chemical composition of PM for some critical emissions sources to improve estimates of BC in these inventories.

4.2 Introduction

Emissions inventories provide valuable information about major sources of BC, both domestically and internationally, and the trends in BC emissions over time. This chapter covers domestic and global emissions of BC and OC. In the case of domestic emissions, the discussion begins with source measurements that generate speciated emissions profiles and ends with a description of the current U.S. emissions inventory for BC and OC by source category, with particular attention to mobile sources, open biomass burning, and fossil fuel combustion.[1] This chapter also provides an overview of key emissions estimates from available global inventories as well as inventories for key world regions such as China and India, and evaluates historical trends in global emissions. This chapter includes a comparison of the U.S. portion of the global BC inventory to the EPA developed estimates. In addition, this chapter discusses the implications of long-range transport of aerosols, which contributes to total BC in the column of air above an area. Based

[1] Most estimates of source emissions in the United States utilize thermal optical methods which estimate BC as elemental carbon (EC). However, for purposes of this chapter, all emissions estimates will be referred to as BC. This issue is addressed for ambient measurements in Chapter 5 and covered in more detail in Appendix 1.

on the discussion in this chapter, key emissions research needs for BC and other light absorbing aerosols are incorporated into the recommendations discussed in Chapter 12.

4.3 U.S. Black Carbon Emissions

4.3.1 Summary of Emissions Methodology

Currently, the U.S. EPA does not require the states to report emissions of BC and other PM constituents (OC, nitrates, sulfates, crustal material) as part of the National Emissions Inventory (NEI). Rather, the U.S. emissions inventory uses total $PM_{2.5}$ emissions to derive estimates for direct emissions of carbonaceous particles, including BC and OC, for all sources except on-road mobile sources. Therefore, all of the available emissions inventory information on carbon emissions in the United States is restricted to those source categories with sufficient $PM_{2.5}$ emissions estimates to support this derivation. The methods used to generate U.S. emissions inventories are described in detail in Appendix 2.

In general, EPA estimates emissions of BC and OC by appropriately matching $PM_{2.5}$ emissions estimates from EPA's NEI with source profiles contained in EPA's SPECIATE database (see Appendix 2 for details). SPECIATE is the EPA's repository of PM and VOC speciation profiles of air pollution sources. The PM speciation profiles contain weight fractions of chemical species (e.g., BC and OC) for specific sources. Applying these profiles to PM emissions inventories provides estimates of how much BC and OC is emitted by specific source categories. There are about 300 profiles in the SPECIATE database that are of sufficient quality for this purpose. The mapping of how these approximately 300 profiles have been applied to the over 3,400 source categories available in EPA's NEI for $PM_{2.5}$ is described in Appendix 2 and more details are available in the literature (Reff et al., 2009; Simon et al., 2010). For all non-mobile source and non-open biomass emissions estimates, all BC and OC estimates are based on EPA's 2005 modeling inventories (termed "2005CK" inventories), which rely on the 2005 NEI for $PM_{2.5}$.

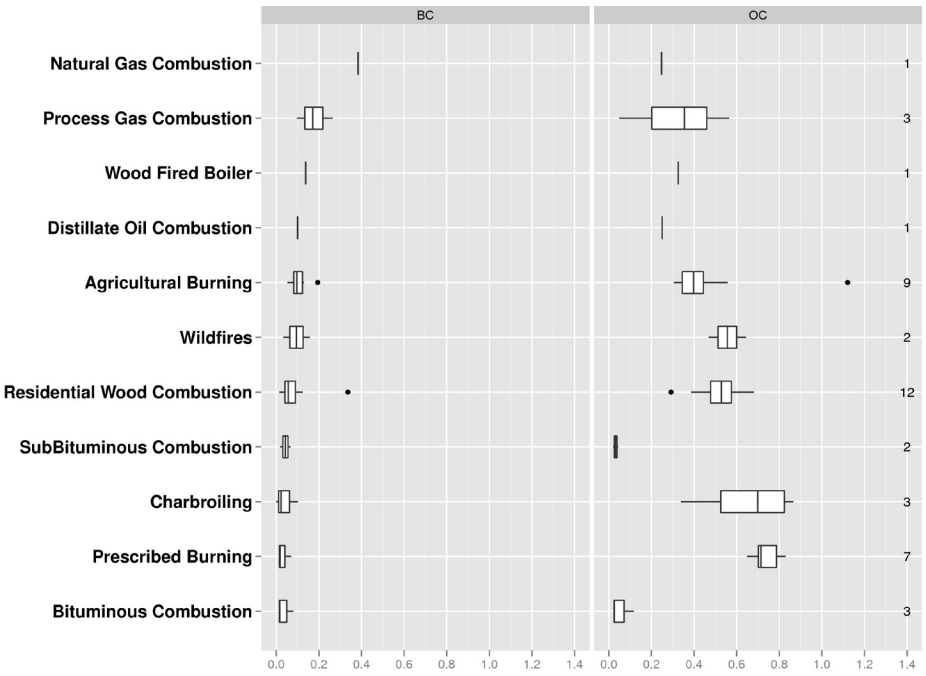

Figure 4-1. BC and OC Fractions of $PM_{2.5}$ Emissions for the Highest BC Emitting Non-Mobile Source Categories in the United States. The box represents the 25th to 75th percentile range and the whiskers represent the 10th and 90th percentile points of the individual source profiles based on emissions source test data as it exists in EPA's SPECIATE database for each source category. The vertical lines within the box represent the median values for that source category. The dots represent outliers. Some of the outliers show a fraction greater than unity; that is due to the statistical procedures used to composite averages. See Appendix 2 for further details. (Source: U.S. EPA)

As noted above, for on-road mobile source categories (e.g., cars and trucks), BC is predicted directly without using SPECIATE. For on-road gasoline and diesel vehicles, emissions estimates are generated directly through models. Appendix 2 provides details on how these emissions were calculated using EPA emissions models for on-road and nonroad vehicles/engines, and also discusses other important issues, like high emitters, deterioration of PM emissions (i.e., increase in PM mass) with age, and increased PM emissions at lower temperatures. All three of these issues are important and available data on them are incorporated

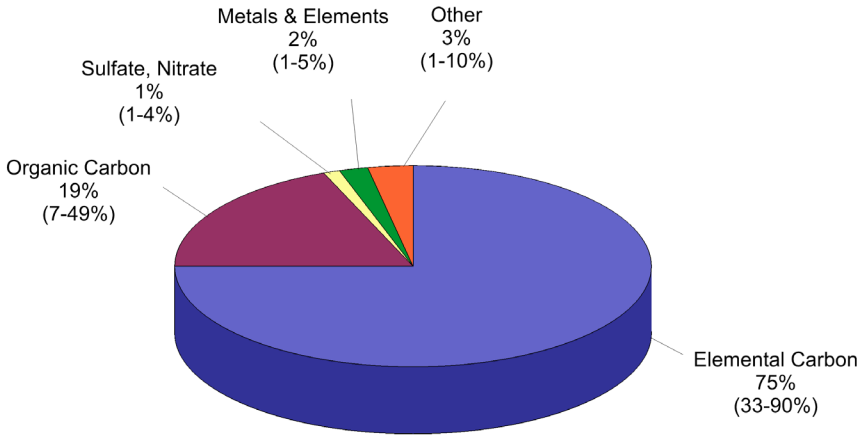

Figure 4-2. Heavy-Duty Diesel $PM_{2.5}$ Emissions Profile.
(Source: U.S. EPA, 2002b)

into EPA's emissions models. There are more data on these issues for gasoline PM than for diesel PM.

$PM_{2.5}$ emissions from open biomass burning (wildfires, agricultural burning, and prescribed burning) come from an emissions inventory compiled by the Regional Planning Organizations (RPOs) for the year 2002 (Regional Planning Organization, 2004a; 2004b; 2005; 2006; 2008). There are five RPOs in the United States which are set up to address regional haze and related issues across the country. Due to the need to accurately represent local/regional fire emissions, each RPO has invested time in including greater regional/local specificity resulting in development of more accurate fire inventories, thereby making them more accurate than national estimates developed by EPA. In addition, these RPO estimates have received more widespread review and acceptance by the states, RPOs and other federal agencies. Though these emissions estimates represent the year 2002, the difference between the year of estimates matters less than the accuracy and review of the estimates; this is because there is very little year-to-year variation in categories besides wildfires. In the case of wildfires, these 2002 estimates are consistent with an average of wildfire activity over a ten year period from 2001 to 2010. BC and OC emissions were then estimated based on these $PM_{2.5}$ estimates using the same methodology explained above. Despite the higher accuracy of RPO emissions estimates as compared to EPA's, it should be noted that biomass burning BC estimates remain more uncertain than engine combustion BC, for example, because of the tremendous year-to-year variability in open burning activity and for other reasons addressed later in this chapter.

It is also important to note that the BC and OC inventories do not account for secondary formation of particles in the atmosphere. While secondary formation is not substantial for BC, a significant amount of OC can be formed in the atmosphere from biogenic and anthropogenic emissions of volatile organic chemicals. Most air quality and climate models rely on estimates of OM (which is OC plus the mass that accrues to primary OC through photochemistry in the atmosphere), rather than OC, to calculate atmospheric reactions and impacts.

Figure 4-1 displays the number of resulting profiles (the numbers on the right-hand side of the graphs) and their distribution of BC and OC fractions of $PM_{2.5}$ by source category. Mobile source categories are not shown in Figure 4-1 due to the fact that BC emissions are estimated directly from models for some of those sources (see below and Appendix 2 for more information on all mobile source categories). The number of individual profiles by source category can be quite limited; sometimes only a single value is known. The source categories depicted on the y-axis in Figure 4-1 are shown top-to-bottom in order of maximum BC fraction to minimum BC fraction. Natural-gas combustion (see caveat later in this chapter) has only one profile available but has the highest BC fraction of the source categories shown in Figure 4-1 while some of the burning and coal combustion categories have the lowest BC fractions.

Heavy-duty diesels have the highest BC fraction of all source categories, at an average of about 77% although this percentage varies depending on operating mode and engine technologies. This fact is supported by the EPA's *Health Assessment Document for Diesel Engine Exhaust* (2002b) in which the chemical composition of diesel engine exhaust is identified as shown in Figure 4-2, with BC contributing 75% of the total $PM_{2.5}$ composition. Light-duty gasoline vehicles have a much smaller fraction (about 20-25%) of PM that is BC.

4.3.2 U.S. Black Carbon Emissions: Overview and by Source Category

In 2005, the United States is estimated to have emitted about 5.5 million tons (or about 5,000 Gg) of primary $PM_{2.5}$ of which about 0.64 million tons (12%) was BC and about 1.7 million tons

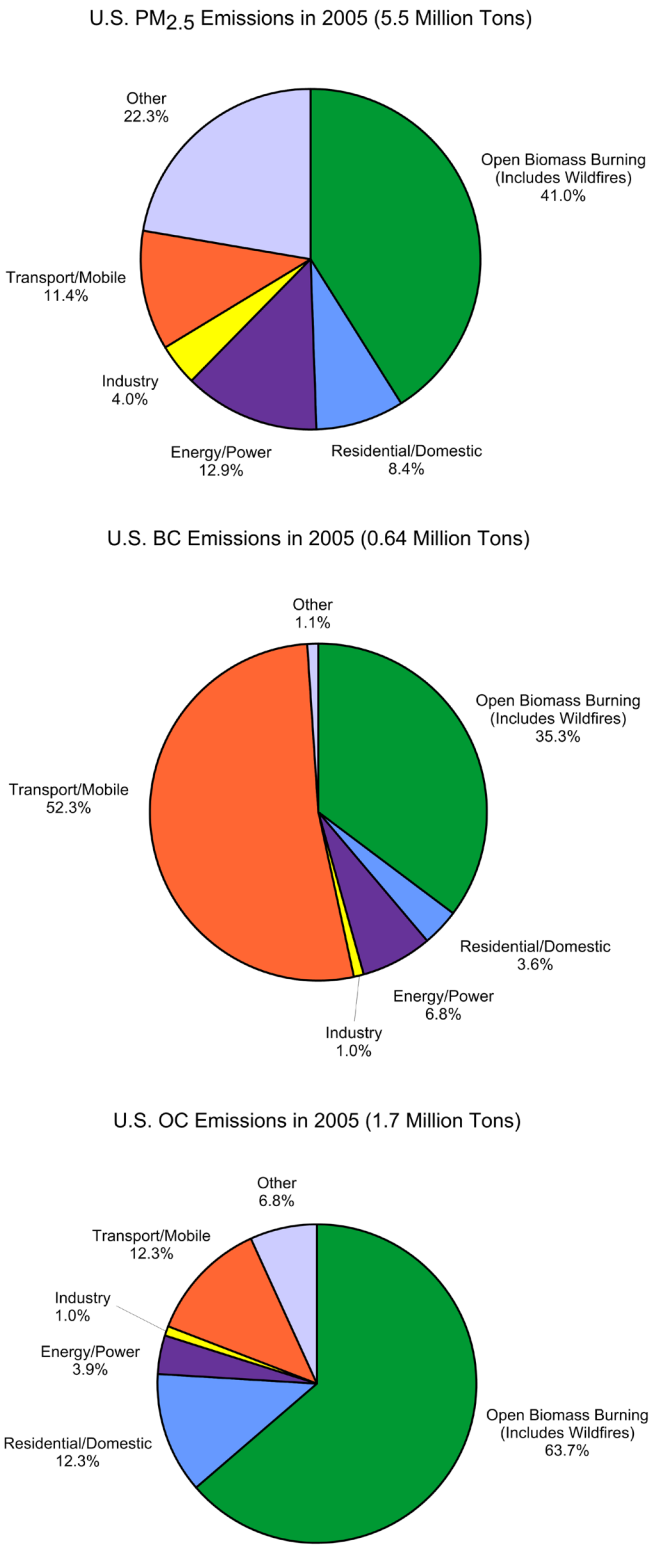

Figure 4-3. Contribution to Primary $PM_{2.5}$, BC, and OC Emissions by Mega Source Categories. (Source: U.S. EPA, 2002a, 2005a)

(30%) was primary OC.[2, 3, 4] Thus at a national level, more than twice as much OC is emitted from domestic sources as BC. The domestic emissions of 0.64 million tons represents about 7% of the world's total BC emissions (i.e., 8.4 million tons) making the United States the 8th largest global BC emitter (Lamarque et al., 2010). The majority of U.S. BC emissions come from mobile sources (predominantly diesel) and open biomass burning. In 2005, about 65% of total U.S. BC was emitted in urban counties and, in the case of mobile sources, more than 70% of the total U.S. BC emissions occur in urban counties. In addition, it should be noted that all emissions estimates shown in this chapter are annual averages. There is expected to be some seasonal patterns in BC emissions for some of the source categories. However, that detail is beyond the scope of this chapter. All emissions numbers are only estimates, as detailed in the Appendices. There are uncertainties in all of these estimates that vary from category to category. Systematic quantitative estimates of uncertainty in U.S. emissions estimates are not available at this time, though some qualitative discussion is provided both in this chapter and in the Appendices.

Figure 4-3 displays the percentage of total U.S. emissions of primary $PM_{2.5}$, BC, and OC for six "mega" source categories:

- Open biomass burning (agricultural burning, wildfires, and prescribed burning)
- Residential (any combustion for residential activities regardless of fuel burned)
- Energy/power (EGUs and other power generation sources)
- Industrial

[2] The U.S. emissions estimates presented in this chapter reflect data from EPA's National Emissions Inventory and mobile source models, supplemented with data from U.S. Regional Planning Organizations (RPOs) on open biomass burning (wildfires, agricultural burning, and prescribed burning). Most estimates presented in this chapter are for the year 2005. However, all emissions estimates for open biomass burning are based on a 2002 inventory developed by the RPOs, which are partially funded by EPA. For ease of reference, these various sources are grouped under the label "U.S. EPA" in figures and tables throughout this chapter. More detail on how different portions of the inventory are constructed is provided in other parts of this chapter and in Appendix 2.

[3] Unless otherwise specified, the term "tons" refers to short tons throughout this report. 1102 short tons = 1 Gigagram.

[4] This does not account for other components of organic PM emissions, such as oxygen and hydrogen.

Table 4-1. 2005 U.S. Emissions (tons) and Ratios of Emissions by Mega Source Category. (Source: U.S. EPA)

Mega Source Category	$PM_{2.5}$	BC	OC	OC/BC	BC/$PM_{2.5}$
Open Biomass Burning	2,266,513	224,608	1,058,494	4.7	0.1
Residential	464,063	22,807	204,160	9	0.05
Energy/Power	712,438	43,524	65,138	1.5	0.06
Industrial	219,460	6,085	16,234	2.7	0.03
Mobile Sources (Transport)	626,859	333,400	205,172	0.6	0.53
Other	1,232,123	6,743	112,967	16.8	0.01
Totals (Short Tons)	**5,521,456**	**637,167**	**1,662,165**	**2.61**	**0.12**
In GigaGrams (Gg)	**(5,009)**	**(578)**	**(1,508)**		

- Transport/mobile (including on-road, nonroad, locomotives, commercial marine, aircraft and tire/brake wear)
- Other

Table 4-1 shows the actual tons per year of direct $PM_{2.5}$, BC, and OC emissions for these source categories, as well as some key emissions ratios. In the last row, emissions in Gigagrams (Gg) are shown in parenthesis, since metric units are standard for reporting global emissions.[5]

Figure 4-3 clearly shows mobile sources are the dominant contributor to total BC emissions in the United States in 2005. Mobile sources contribute 52% of the total BC emissions, followed by open biomass burning (35%),[6] and energy/power (7%). All other categories are about 4% or less. Additional detail on the specific sources that comprise these mega source categories is provided later in this section.

As shown by the ratios in Table 4-1 (OC/BC and BC/$PM_{2.5}$), the composition of primary $PM_{2.5}$ emissions varies significantly among source categories. As discussed in Chapter 2, such differences have important implications for climate. For example, diesel-powered mobile sources emit significantly more BC than OC, while the opposite is true for open biomass burning and residential sources. Figure 4-4 displays the total BC emissions for the different source categories. The data in Table 4-1 also show that for some source categories, BC and OC together make up less than 50% of total $PM_{2.5}$ emissions, indicating that there are significant amounts of other/unidentified primary co-pollutants (such as direct emissions of nitrates and sulfates) in the emissions mixture.

The mega source categories can be subdivided into more specific categories. Table 4-2 shows the national-level emissions of primary $PM_{2.5}$, BC, and OC emissions for about 90 specific sub-categories

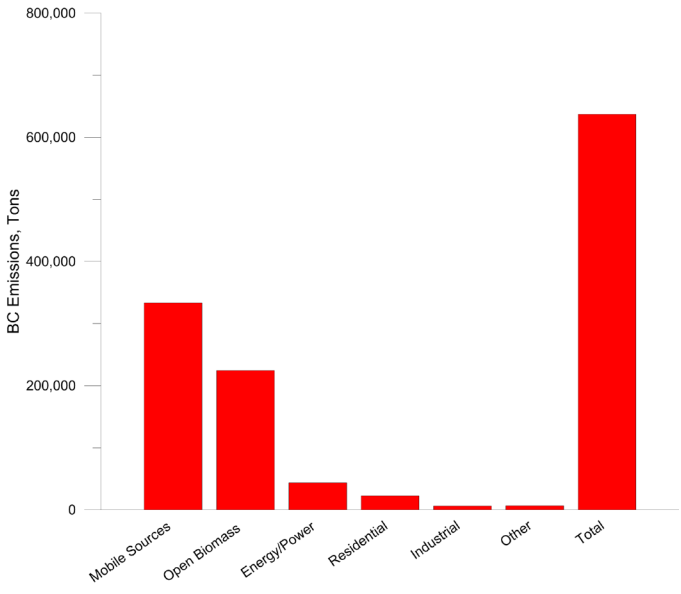

Figure 4-4. U.S. BC Emissions (tons) for Major Source Categories. (Source: U.S. EPA)

[5] In global inventories, total emissions are often grouped into two main categories, "open" vs. "contained" (or "closed"). To avoid confusion among these terms in this report, the term "contained combustion" is used to refer to all sources except open biomass burning. This is consistent with the global emissions inventory literature. "Contained combustion" is a broadly encompassing term, referring to all combustion sources in which fuel is burned in a chamber or controlled environment (including sources such as industrial/EGU boilers, internal combustion engines, stationary diesel engines, and contained burning of biomass in sources such as wood-fired boilers).

[6] This total includes wildfires. The distinct contributions of wildfires and agricultural/prescribed fires to total domestic emissions of primary $PM_{2.5}$, BC and OC are provided in Table 4-2.

Table 4-2. U.S. Emissions of $PM_{2.5}$, BC, and OC (short tons). (Source: U.S. EPA)

Mega Source Category	Specific Category	Total Primary $PM_{2.5}$	BC	Primary OC	OC/BC	BC/$PM_{2.5}$
Open Biomass	Wildfires	1,600,358	151,855	738,997	4.9	0.09
	Prescribed Burning	535,627	58,525	268,826	4.6	0.11
	Agricultural Burning	130,528	14,228	50,671	3.6	0.11
Residential	Residential Wood Combustion	379,878	21,194	200,645	9.5	0.06
	Residual Oil Combustion	78,672	787	787	1	0.01
	Residential Coal Combustion	2,648	634	1,187	1.9	0.24
	Residential Natural Gas Combustion	2,865	192	1,541	8	0.07
Energy/Power	Natural Gas Combustion	64,239	24,668	15,867	0.64	0.38
	Bituminous Combustion	394,853	6,697	10,387	1.6	0.02
	Sub-Bituminous Combustion	143,383	6,028	4,514	0.7	0.04
	Distillate Oil Combustion	23,718	2,372	5,930	2.5	0.1
	Wood Fired Boiler	56,289	2,088	19,764	9.5	0.04
	Process Gas Combustion	9,457	1,378	2,850	2	0.15
	PMSO2 Controlled Lignite Combustion	20,499	293	5,826	19.9	0.01
Industrial	Stationary Diesel	4,476	3,452	786	0.2	0.77
	Cement Production	17,523	514	2,221	4.3	0.03
	Ind Manuf - Avg.	46,501	416	3,422	8.2	0.01
	Mineral Products - Avg	23,632	347	1,242	3.6	0.01
	Kraft Recovery Furnace	21,222	325	1,111	3.4	0.02
	Chem Manuf - Avg	17,526	320	1,608	5	0.02
	Lime Kiln	7,002	162	466	2.9	0.02
	Heat Treating	14,439	144	1,011	7	0.01
	Aluminum Production	5,730	132	223	1.7	0.02
	Ferromanganese Furnace	1,240	125	64	0.5	0.1
	Surface Coating	9,165	64	1,903	29.7	0.01
	Cast Iron Cupola	3,479	32	222	6.9	0.01
	Electric Arc Furnace	4,317	16	140	8.8	0
	Secondary Aluminum	6,057	12	91	7.6	0
	Sintering Furnace	5,739	10	157	15.7	0
	Pulp & Paper -Avg	6,569	7			0
	Catalytic Cracking	8,864	6	1	0.2	0
	Secondary Copper	1,137	1	11	11	0
	Ammonium Nitrate Production	1,025				0
	Secondary Lead	410				0
	Petroleum Ind - Avg	6,224		218		0
	Copper Production	432				0
	Ammonium Sulfate Production	65				0
	Open Hearth Furnace	6,686		1,337		0

Mega Source Category	Specific Category	Total Primary $PM_{2.5}$	BC	Primary OC	OC/BC	BC/$PM_{2.5}$
Mobile Sources	On-road diesel	208,473	153,477	44,423	0.3	0.74
	Nonroad diesel	145,289	112,058	30,618	0.3	0.77
	Locomotive	30,910	22,495	5,130	0.2	0.73
	Commercial Marine (C1 & C2)	28,119	21,652	4,937	0.2	0.77
	On-road gasoline	75,924	14,510	59,657	4.1	0.19
	Nonroad gasoline	55,834	5,444	46,734	8.6	0.1
	Commercial Marine (C3)	56,028	1,681	6,303	3.7	0.03
	Tire	5,325	1,198	3,060	2.6	0.22
	Brakewear	17,801	475	2,321	4.9	0.03
	Aircraft	3,156	410	1,988	4.8	0.13
Other	Charbroiling	64,124	2,601	42,975	16.5	0.04
	Wood Products - Drying	8,113	649	4,057	6.3	0.08
	Paved Road Dust	54,481	569	5,308	9.3	0.01
	Dairy Soil	9,862	509	3,139	6.2	0.05
	Wood Products-Sawing	12,355	469	5,498	11.7	0.04
	Overall Average Manufacturing	10,577	466	927	2	0.04
	Unpaved Road Dust	419,648	409	22,897	56	0
	Charcoal Manufacturing	5,578	290	100	0.3	0.05
	Solid Waste Combustion	14,965	228	1,258	5.5	0.02
	Wood Products - Sanding	2,257	135	790	5.9	0.06
	Asphalt Manufacturing	2,160	124	93	0.8	0.06
	Fiberglass Manufacturing	4,641	93	1,299	14	0.02
	Agricultural Soil	334,515	67	10,310	153.9	0
	Fly Ash	1,733	30	21	0.7	0.02
	Phosphate Manufacturing	992	27	78	2.9	0.03
	Industrial Soil	2,011	23	20	0.9	0.01
	Food & Ag - Handling	10,331	18	418	23.2	0
	Urea Fertilizer	589	12	183	15.3	0.02
	Potato Deep-Frying	192	8	121	15.1	0.04
	Glass Furnace	7,803	5	55	11	0
	Calcium Carbide Furnace	314	4	23	5.8	0.01
	Sludge Combustion	163	2	14	7	0.02
	Crustal Material	1,160	2	62	31	0
	Brick Grinding and Screening	1,272	1	31	31	0
	Auto Body Shredding	129	1	10	10	0.01
	Inorganic Fertilizer	78	1	2	2	0.01
	Asphalt Roofing	1,872	0	1,129		0
	Limestone Dust	1,912				0
	Sand & Gravel	134,885				0
	Construction Dust	96,669		4,463		0
	Meat Frying	12,216		7,012		0
	Lead Production	33				0

Mega Source Category	Specific Category	Total Primary $PM_{2.5}$	BC	Primary OC	OC/BC	BC/$PM_{2.5}$
Other	Synthetic Residential Wood Combustion	345				0
	Sandblasting	1,673		8		0
	Steel Desulfurization	259				0
	Inorganic Chemical Manufacturing	4,161				0
	Gypsum Manufacturing	1,395				0
	Food & Ag-Drying	5,551		666		0
	Boric Acid Manufacturing	11				0
	Coke Calcining	811				0
	Sea Salt	287				0

Notes:

1. All emissions are for 2005 except those for "open biomass burning," which are based on 2002 RPO estimates (as referenced earlier).
2. This table represents all emissions in column D as BC; however, they were derived from thermal-optical monitoring techniques and reported as EC.
3. Blank cells indicate that the profiles used showed no BC emissions from these sources.
4. Aircraft inventories only include emissions from landings and take-offs and do not include in-flight emissions.
5. In this table, the mobile source inventories are for all 50 states. Wildfire emissions are for the 48 contiguous states plus Alaska. All other estimates are only for the 48 contiguous states (AK and HI are expected to be minor BC and OC contributors for all these sources).
6. BC emissions from "Agricultural Burning" are very dependent on the types of burning activity included (e.g., range land, crop residue, and other types of burning activity). The data used in this report to characterize prescribed burning includes range land and crop residue burning activity as well as other types. Other recent work using satellite-imagery shows the total "agricultural emissions" in the United States (averaged over 5 years) are somewhat lower than the BC emissions estimates shown here (McCarty, 2011). McCarty's estimates for BC emissions from agriculture burning are based on the inclusion of crop residue burning only and PM emission factors for that type of burning. This is a limited definition of "agricultural burning" that others also feel is appropriate. Working with USDA, EPA is in the process of evaluating this work as well as more of its own recent work on a 2008 fires inventory that relies on updated remote sensing methods to estimate emissions from agricultural burning.

of sources in the United States. Table 4-2 also shows OC/BC and BC/$PM_{2.5}$ ratios for each of the specific source categories. Some of these data are drawn from the NEI, EPA's "bottom-up" compilation of estimates of air pollutants discharged on an annual basis and their sources (U.S. EPA, 2005a). As discussed previously, the "open biomass burning" categories shown in yellow come from an emissions inventory compiled by the RPOs for the calendar year 2002 (Regional Planning Organization, 2004a; 2004b; 2005; 2006; 2008).

4.3.2.1 Emissions from Mobile Sources

Mobile sources account for about 52% of total U.S. BC emissions in 2005. Within this category, emissions from diesels (both nonroad and on-road) dominate, accounting for about 93% of BC. Gasoline vehicles/engines are responsible for most of the remaining BC emissions from the mobile source category. Figure 4-5 shows this more detailed breakout of mobile source BC emissions. In general, diesel $PM_{2.5}$

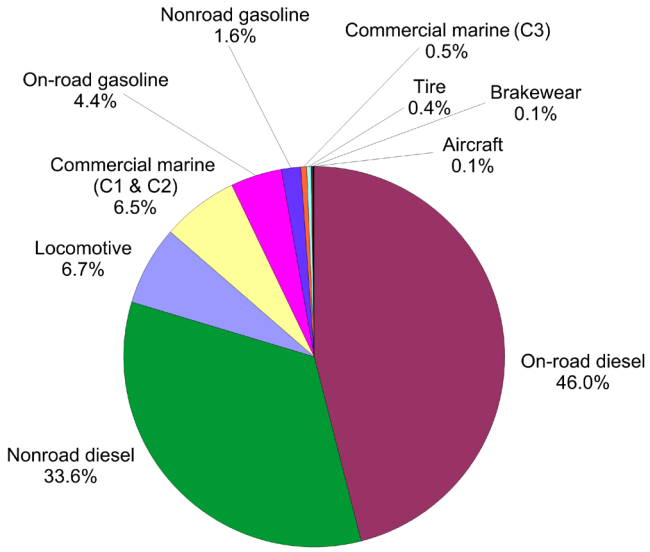

Figure 4-5. U.S. BC Emissions from all Mobile Source Categories (333,400 tons). (Source: U.S. EPA)

consists of about 70-80% BC and about 20% OC.[7] Gasoline $PM_{2.5}$, in contrast, consists of about 20% BC with the remainder being mostly OC. The BC/PM fraction though varies by operating condition such as cold start, high speed/load, and normal driving. Also, as discussed in Appendix 2, diesels used for large (ocean-going) commercial marine vessels have much lower BC/PM fractions due to the high amount of organics and sulfates. Diesel PM is unique in having a very high ratio of BC to OC. The total light absorbing capacity of the specific compounds and the resultant mixture emitted in diesel or gasoline exhaust is not known. However, several mobile source measurements suggest that particle emissions from both gasoline and diesel vehicles are strongly light absorbing (Japar et al., 1984; Strawa et al., 2010; Adler et al., 2010; Japar and Szkarlat, 1980). It should be noted that while mobile sources represent about 52% of the national total of BC emissions, they represent about 69% of all non-wildfire BC emissions in the United States.

While mobile sources dominate the U.S. inventory currently, significant reductions in emissions of both BC and OC have been achieved since 1990, and existing vehicle regulations are expected to produce further reductions in coming years as they are implemented. Most of these BC reductions are a direct result of EPA's regulations on diesel PM, but reductions in total carbon emissions, mostly OC, are also due to regulations on emissions from gasoline vehicles. Due to these regulations, the mobile source contribution to BC compared to other sources has declined on both an absolute basis and a fractional basis since 1990. As reductions continue through 2030 and beyond, the pie chart shown in Figure 4-3 will continue to change, showing an increasingly smaller contribution of mobile sources to overall U.S. BC emissions. Chapter 8 summarizes mobile source BC inventories for various years from 1990 through 2030, and the control programs that are expected to result in these emissions reductions by 2030.

Numerous source apportionment studies have been done for local areas in the United States including Denver, Los Angeles, Atlanta, Phoenix, and other areas (Watson et al., 1998; Zheng et al., 2007; Brown et al., 2007). These studies show the importance of mobile source emissions to ambient $PM_{2.5}$ (and in some cases, BC) levels, just as various emissions inventories do. The inventories in this report are nationwide inventories and, thus, are not comparable to source apportionment studies which are done in local areas. Also, there are various workshops and studies looking at differing health impacts of PM components including some health studies on source apportionment (Thurston et al., 2005; Marmur et al., 2006).

4.3.2.2 Emissions from Biomass Combustion

Several source categories in Table 4-2 include emissions from "wood based" (biomass) combustion. Based on an approach suggested by Bond et al. (Bond, 2007; Bond et al., 2004) to facilitate consideration of mitigation options, elements of these source categories: "open biomass burning", "residential heating/cooking", and "biomass fired stationary sources" have been combined into a "biomass combustion" category for this discussion. Table 4-3 summarizes the sources included this "biomass combustion" category and their associated emissions.

These biomass combustion sources are estimated to collectively emit a little more than 250,000 tons of BC annually. This represents about 39% of the total amount of BC emitted in the United States, second only to mobile sources in terms of contribution to total domestic BC. The 1.2 million tons of OC emissions from these biomass combustion sources represent about 75% of the total amount of OC emitted in 2005 domestically.[8]

About 90% (roughly 225,000 tons) of total biomass combustion emissions of BC in the United States comes from ''open biomass burning" sources (Figure 4-6). Wildfires contribute about 60% (152,000 tons) to the "biomass combustion" source total with emissions from Alaskan wildfires alone representing about 33% of all biomass combustion emissions in the United States. Emissions from wildfires can vary greatly from year to year (Figure 4-7); however, this single year estimate of 2002 emissions is consistent with an average of wildfire activity in the United States over the ten year period from 2001 to 2010. About 9% (or 21,000 tons) of the national biomass combustion total is emitted by residential wood combustion (from "residential heating/cooking"), and less than 2% (about 5,000 tons) from wood fired boilers and charbroiling (from "other" sources).

[7] The estimate shown applies to the total diesel PM inventory. However, under low loads (e.g., idle), BC constitutes a smaller fraction of PM emissions (i.e., 20-40%). Emissions in these conditions contribute a relatively small fraction of total PM.

[8] Often, global inventories define a broad "contained burning" source category that includes the following sources from Table 4-2: all of the sources listed in the "Residential" mega category, "wood fired boilers" in the "Energy/Power" mega category, and "charbroiling" in the "Other" mega category (Bond, 2007; Bond et al., 2004). For the United States, "contained burning" sources defined in this way emit about 27,000 tons of BC combined (in 2005), which represents about 11% of the BC emissions and about 20% of the OC emissions from all biomass combustion (open and contained) that occurs in the United States.

Table 4-3. National Level U.S. Emissions of PM2.5, BC, and OC for Biomass Combustion Sources in 2002/2005 (short tons). (Source: U.S. EPA)

General Category	Specific Source	Total Primary $PM_{2.5}$	BC	OC	OC/BC	$BC/PM_{2.5}$	Mega Source Category in Table 4-2
Open Biomass Burning	Agricultural Burning	130,528	14,228	50,671	4	0.11	Open Biomass
	Wildfires	1,600,358	151,855	738,997	5	0.09	
	Prescribed Burning	535,627	58,525	268,826	5	0.11	
	Subtotal	**2,266,513**	**224,608**	**1,058,494**	**4.7**	**0.1**	
Residential Heating/ Cooking	Residential Wood Combustion	379,878	21,194	200,645	9.5	0.06	Residential
	Subtotal	**379,878**	**21,194**	**200,645**	**9.5**	**0.06**	
Other	Wood Fired Boiler	56,289	2,088	19,764	9	0.04	Energy/Power
	Charbroiling	64,124	2,601	42,975	17	0.04	Other
	Subtotal	**120,413**	**4,689**	**62,739**	**13.4**	**0.04**	
Biomass Consumption Total		**2,766,804**	**250,491**	**1,321,878**	**5**	**0.09**	

Unlike diesel mobile sources, OC/BC ratios for biomass combustion sources are generally much greater than one, indicating a predominance of OC emissions (about 80% on average). Table 4-3 further evidences a smaller OC/BC ratio (on average) for "open biomass burning" than for the other categories of biomass burning; however, the OC/BC ratios are reasonably consistent at about 4 or 5 within the "open burning" categories. While the relatively high OC/BC ratios shown in Table 4-3 for most of these sources may suggest that they do not represent the best mitigation candidates for climate purposes, it should be noted that OC emissions from biomass burning may contain more light-absorbing organic carbon ("brown" carbon) than other sources in general (Hecobian et al., 2010; Moosmüller et al., 2009). Exactly how much of the inventoried OC is light-absorbing is not known at this time.

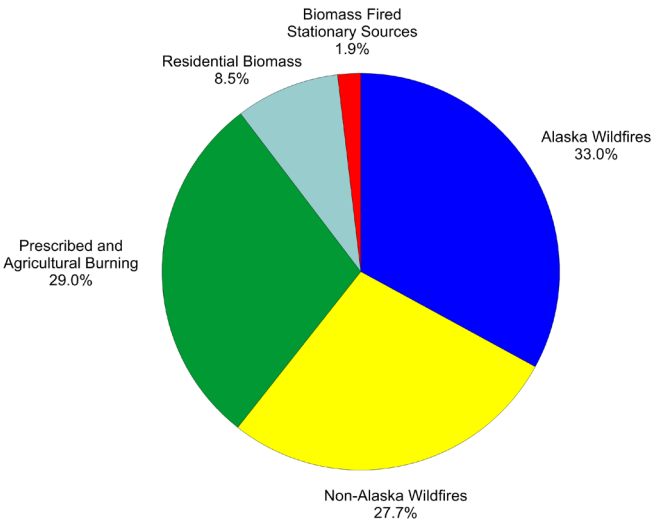

Figure 4-6. U.S. BC Emissions from all Biomass Combustion Source Categories (250,000 short tons). (Source: U.S. EPA)

More than half of U.S. BC emissions from wildfires come from Alaskan fires; due to the close proximity of these emissions to the Arctic, it is likely they would impact the Arctic ice and snow. As discussed in Chapter 2, both BC and OC emissions would be expected to affect Arctic ice melt. However, as noted above, Alaskan wildfire activity is highly variable from year to year and peak emissions occur during the mid-summer season, when they are less likely to influence the Arctic due to prevailing transport patterns during the summer. In addition, fire is a natural ecological process in many ecosystems (see Chapter 11).

4.3.2.3 Emissions from Energy/Power Sector

The energy/power source category contributes approximately 7% of U.S. BC emissions and includes a range of emissions categories, as shown in red in Table 4-2. In general, emissions from these sources are split fairly evenly between BC and OC. The largest fossil fuel combustion source of BC emissions according to the 2005 NEI is natural gas

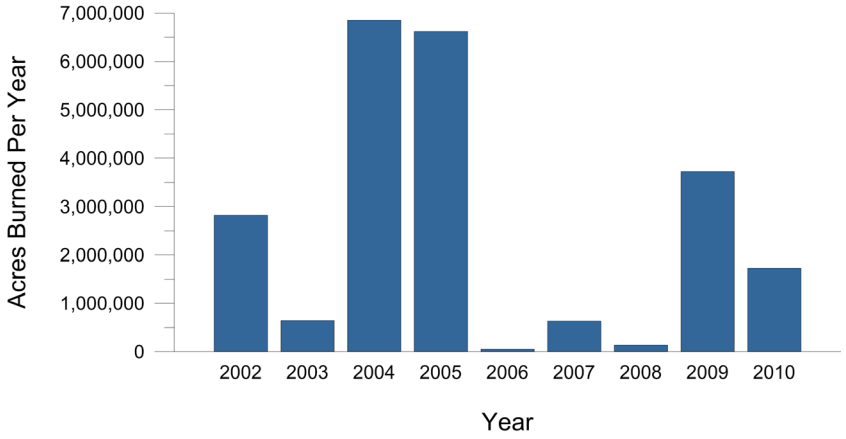

Figure 4-7. Acres Burned per Year in Alaskan Wildfires, 2002-2010. (Source: U.S. Department of the Interior, Wildland Fire Management Information (WFMI) system, *https://www.nifc.blm.gov/cgi.WfmiHome.cgi*)

combustion; however, estimates of the amount of BC compared to OC in direct $PM_{2.5}$ emissions from this source category are highly uncertain.[9] The bituminous and sub-bituminous coal categories, both of which primarily represent electricity generating units (EGUs) but may also reflect small contributions from commercial and institutional sources, represent relatively small contributions to BC emissions in the United States (a little more than 1% each). This small BC contribution is quite different from these sources' contribution to emissions of long-lived GHGs, where they dominate the inventory (e.g., EGUs account for 40% of CO_2 emissions).

4.3.2.4 Emissions from "Other" Source Categories

Table 4-2 shows that the remaining mega categories, "Industrial Sources," and "Other Sources" (in blue and white, respectively), combine to comprise about 2% of total BC emissions domestically. As is explained in more detail in Chapter 9, direct $PM_{2.5}$ emissions from industrial sources in the United States are small compared to emissions of other co-emitted pollutants such as NO_x, HAPs, and CO_2. This is the result of effective control technologies for PM emissions on a variety of stationary/industrial sources. One industrial source of potential interest for additional PM controls is stationary diesel engines (generators, emergency equipment, etc.), which as shown in Table 4-2, has a low OC/BC ratio and contributes more than half of the EC emissions in the "Industrial Sources" category. Existing EPA regulations for new engines in this category are resulting and will continue to result in BC reductions mainly through the use of diesel particulate filters (DPF), although these regulations and resultant controls do not apply to existing engines produced before the model year in which these regulations became effective. Also included in the "other" category are many manufacturing activities as well as fugitive dust emissions sources and charbroiling.

4.4 Global Black Carbon Emissions

Global inventories are important for providing information on the distribution of BC emissions world-wide and for identifying key differences between regions, both in terms of total quantity of emissions and major sources. There are a few global BC inventories available currently, and those from Bond et al. (2004; Streets et al., 2004) are the most widely used and referenced. Compiling a global BC inventory is difficult for several reasons: varying emissions among similar sources, varying measurement techniques, different PM size cut points used in the measurements, and the definition of BC itself (as discussed in other parts of this report) used in the inventories. The most up-to-date of these inventories is for the year 2000 and has been developed to support climate modeling needs in the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment report (termed "AR5"). These estimates have been published in the literature (Lamarque et al., 2010) and form the basis for all the discussion in this section. These estimates effectively serve as "current" year, annual global BC inventories.

In general, these global BC inventories are compiled using fuel-consumption data to estimate emissions from particular source categories. A few global inventories are based on a "top-down" concept (Parrish, 2006; Penner et al., 1993) in which emissions are inferred from concentration and ancillary measurements in the ambient air, usually downwind from the source or calculated from generalized emission factors and national or regional activity

[9] Specifically, EPA applies just one speciation factor to convert direct $PM_{2.5}$ emissions from natural gas combustion sources to estimated EC emissions. This single factor is a $BC/PM_{2.5}$ ratio of 0.38 which leads to a relatively large BC emissions estimate (about 25,000 tons). Though not currently available in the literature, some unofficial source testing has suggested the $BC/PM_{2.5}$ ratio is in the range of 6 to 10% (corresponding to speciation factors of 0.06 to 0.10) indicating that both the combustion process used as well as presence of controls on the unit will affect the amount of BC in $PM_{2.5}$ emissions from this source type. Future work will include further investigation into speciation for this source type.

indicators. Most global inventories, including those of Lamarque et al. (2010) and Bond et al. (2004), used as the basis for this section are based on "bottom-up" type processes. EPA's inventories are also based on "bottom-up" approaches.[10] In this method, emissions are measured or computed directly by concentration, mass flow, and or stream velocity observations at the source, or emissions are calculated (using specific emission factors and activity levels) on a source-by-source or localized basis. Details on methods used to generate both global and domestic BC emissions can be found in Appendix 2, including more details on "bottom-up" approaches.

Global BC inventories have clear advantages when comparing emissions across world-regions, countries, and sectors because the methodology used is consistent across the spatial domain. Global inventories, however, can sometimes overlook important but subtle differences between countries through reliance on default-type information to estimate emissions where actual data are not available. Regional or country-specific inventories, on the other hand, generally contain more accurate emissions information for the domain in question because of the availability of more relevant and more specific data on fuel composition, technology differences in sectors, regulations, emission factors, and activity levels. In this way, the relative importance of certain sources, especially smaller ones, can be incorporated with more accuracy into the final emissions estimates. Unfortunately, each regional inventory tends to employ different methods, making comparisons across regional inventories more difficult. Ideally, regional inventory information could be combined with global inventories to fill in the gaps where global inventories are weakest. While that harmonization has not yet fully occurred, the BC inventories described by Lamarque et al. (2010), below, make an attempt to combine some of the information across global and regional inventories.

This next section provides details on global BC inventories, including the AR5 inventory. It also explores available regional inventories and compares them to global inventory estimates for the same regions. The focus of the regional comparisons will be on Asia, where numerous regional efforts are on-going.

[10] As an example of how these methods arrive at similar conclusions, EPA's motor vehicle emissions model (MOVES) accurately predicts national consumption of gasoline and diesel fuels based on vehicle population and activity data. Differences between EPA and global inventories may therefore be related to differences in underlying emission rates per unit activity or fuel consumption.

4.4.1 Summary of Global Black Carbon Emissions by Region and Source Category

Total global BC emissions for 2000 are estimated to be about 7,600 gigagrams (about 8.4 million tons) for 2000. The spatial distribution of these emissions represented in Figure 4-8 shows Asia, parts of Africa, and parts of Latin America (Central and South America) to be among the regions emitting the largest amounts of BC. Figure 4-9 shows global estimates disaggregated into the these three major world regions responsible for 75% of worldwide BC emissions: (1) Asia (China, India, Southeastern Asia, South Asia, Thailand, Asia-"Stan", Taiwan, Japan, and N. Korea world regions); (2) Africa (Western Africa, Southern Africa rest of, Eastern Africa, Northern Africa, South Africa world regions); and (3) Latin America (South America, Mexico, Central America, Argentina, Venezuela, and Brazil world regions). Asia accounts for about 40% of the global BC emissions, Africa for about 23%, and Latin America for about 12%, as shown in Figure 4-9. Based on these AR5 emissions estimates, the United States accounts for approximately 5% of the global total (i.e., the United States is the 7th most significant region in the world in terms of BC contribution).[11]

Table 4-4 displays total global BC emissions by 37 world regions and by 8 major source categories. Similarly, Table 4-5 shows the distribution of the roughly 35,700 Gg (about 39 million tons) in global OC emissions by these same world regions and source categories. The OC emissions from the United States make up about 3% of the global total.[12] The last column in Table 4-4 shows the ratio of BC emissions from each country or region to those estimated for the United States. For example, China (which comprises nearly all the "East Asia" Region) emits 3.5 times as much BC as the United States.[13] It should be noted that uncertainties/ variability in the inventories (both U.S. inventories and global inventories) could confound the ratios presented in the last column in Tables 4-4 and 4-5. The ratios in those tables are simply ratios of the sum total estimate of emissions for the country in question to the U.S. estimate (using the same methods). Source-specific uncertainties could play a role in the overall ranking of a country's contribution to the total global burden of BC emissions (this

[11] U.S. EPA estimates of U.S. BC emissions are about 49% higher than those from AR5, which would suggest that the U.S. actually contributes approximately 8% to global BC emissions. These differences are more fully discussed later in this chapter.

[12] EPA estimates OC emissions at about 4% of the global total.

[13] If EPA-based estimates are substituted for the AR5 estimates of U.S. BC emissions, the ratio of China to U.S. BC emissions is closer to 2.3.

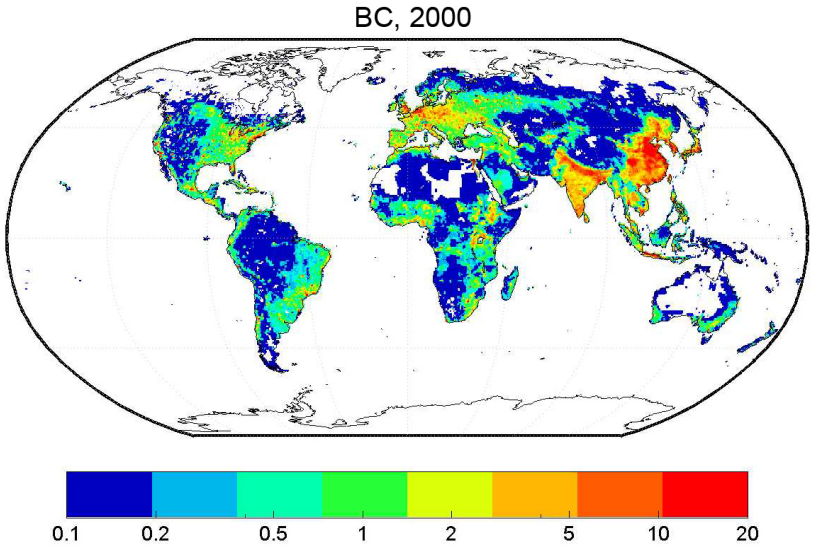

Figure 4-8. Global BC Emissions based on Year 2000 Estimates, in Gigagrams (Gg). (Courtesy of Tami Bond, produced based on data from Bond et al., 2007)

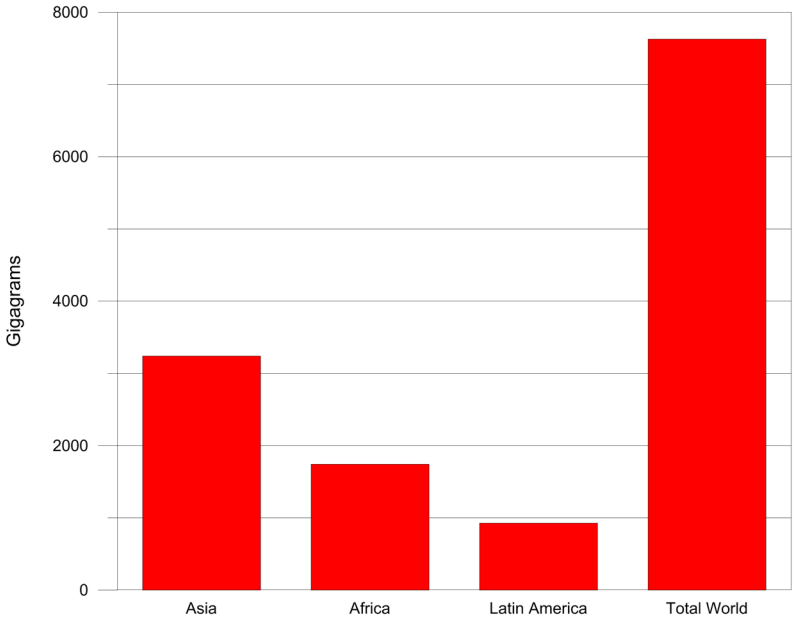

Figure 4-9. BC Emissions by Selected World Region, 2000 (Gg). (Source: Lamarque et al., 2010)

point applies to many of the graphs shown below and is discussed further in section 4.4.4); however, evaluation of how uncertainty plays a role in these ratios and ranking is beyond the scope of this report. While EPA has not done an uncertainty analysis on its inventories, recent work by others (Chow et al., 2011) has looked into the variability in source profiles of BC and OC for the various U.S. source categories to develop a range of emissions estimates instead of just one number. More work along these lines needs to be done in the future for all emissions estimates to have a better understanding of which sectors vary in emissions the most and how that variation plays a role in the estimation of emissions.

Developed world regions like Europe, Japan, and the Middle East have very low BC emissions. In these regions, like in the United States, transportation is the dominant emissions sector. Japan also has significant contributions to BC from industrial sources. In identifying mitigation options, care must be exercised when relying on classifications of world regions/ countries as either "developed" or "developing" as surrogates for BC emissions intensity or source to determine how "climate-beneficial" controls might be. China, for example, has the fastest growing economy in the world, yet has a developing country's level of per capita income. While China shares the high BC emissions levels of less developed countries, its sources of BC are not the same as those of less developed areas. A crucial difference between China and other developing areas is China's use of coal in residential combustion, as well as poorly controlled emissions from industry, and apparently a much lower reliance on burning in agriculture than is typical. This makes the contribution to potential warming due to BC emissions greater for China but suggests the most suitable mitigation approaches in China would be different than in other developing countries.

Figure 4-10 groups the global emissions reported in Table 4-5 into six broad source categories, and indicates that global BC totals are dominated by open biomass burning, and residential cooking and heating sources. Roughly 35% of the total global emissions of BC are from open biomass burning, while the domestic (or residential) sector contributes 25% of the global total. In developing countries, most

Table 4-4. Global BC Emissions in 2000 (in Gg). Transport Includes Aircraft and Shipping. (Source: Lamarque et al., 2010)

Region	Energy	Industry	Transport	Residential / Domestic	Ag Waste Burning	Waste	Grassland Fires	Forest Fires	Total	Country/US Ratio
China	12	669	72	539	44	7	5	9	1,358	3.48
Western Africa	0	20	15	127	8	3	505	105	784	2.01
India	4	108	74	324	4	2	5	15	538	1.38
Brazil	1	53	91	30	3	2	70	215	465	1.19
Southern Africa (Rest of)	0	8	5	68	2	0	373	4	460	1.18
Indonesia	1	28	34	73	12	1	7	252	407	1.04
USA	3	85	216	55	6	3	9	13	390	1
Russia	5	33	32	102	7	1	35	145	360	0.92
Eastern Africa	0	5	7	119	4	1	210	7	353	0.9
Southeastern Asia (Rest of)	1	30	45	101	3	1	6	166	353	0.9
South America (Rest of)	0	20	34	30	5	1	42	45	178	0.46
Australia	0	11	12	7	4	0	120	20	174	0.45
Western Europe (Rest of)	1	36	88	17	1	1	6	1	150	0.39
Central Europe (Rest of)	3	26	40	54	2	1	2	3	131	0.34
Japan	2	49	61	7	1	1	0	1	123	0.32
South Asia (Rest of)	0	13	30	68	0	1	1	2	116	0.3
Middle East	3	37	62	2	6	1	0	0	111	0.29
South Korea (Republic of Korea)	3	55	36	9	3	1	0	0	106	0.27
Mexico	3	13	36	6	5	1	8	28	99	0.26
Northern Africa	0	11	36	37	1	1	0	0	87	0.22
Central America	0	15	16	12	1	1	2	35	84	0.21
Thailand	0	20	33	12	2	0	3	12	83	0.21
Canada	0	17	19	4	2	0	5	31	78	0.2
France	1	10	48	11	0	0	0	0	71	0.18
Ukraine	0	14	9	40	5	0	1	1	71	0.18
Argentina	0	12	26	6	7	0	14	4	70	0.18
Germany	1	13	48	5	0	1	0	0	68	0.17
Asia-"Stan"	0	10	2	27	2	0	25	0	67	0.17
South Africa	1	10	14	16	1	0	16	0	58	0.15
United Kingdom	1	10	31	4	0	0	0	0	46	0.12

Region	Energy	Industry	Transport	Residential / Domestic	Ag Waste Burning	Waste	Grassland Fires	Forest Fires	Total	Country/US Ratio
Italy	2	9	31	2	0	0	1	0	46	0.12
Taiwan	1	18	12	2	0	0	0	0	32	0.08
Venezuela	0	5	7	0	1	0	8	9	30	0.08
Turkey	1	12	10	2	4	0	0	0	30	0.08
North Korea (Democratic Peoples Republic)	0	11	1	16	0	0	0	1	29	0.07
Baltic States (Estonia, Latvia)	0	1	3	11	0	0	0	1	15	0.04
New Zealand	0	1	3	1	0	0	0	0	6	0.01
World Total	**54**	**1,497**	**1,340**	**1,947**	**146**	**35**	**1,481**	**1,128**	**7,628**	

Table 4-5. Global OC Emissions in 2000 (in Gg). Transport Includes Only Aircraft. Global OC Emissions Estimates Not Available for Shipping. (Source: Lamarque et al., 2010)

Region	Energy	Industry	Transport	Residential/ Domestic	Ag Waste Burning	Waste	Grasssland Fires	Forest Fires	Total	Country/US Ratio
Western Africa	1	104	43	538	41	3	3,679	882	5,291	6.37
Indonesia	5	34	63	327	57	1	51	3,060	3,595	4.33
Russia	25	23	33	550	34	3	338	2,582	3,588	4.32
China	39	877	72	1,812	208	7	37	122	3,174	3.82
Southern Africa (Rest of)	0	24	9	275	7	0	2,732	34	3,083	3.71
Brazil	8	203	103	85	14	2	487	1,788	2,690	3.24
Eastern Africa	0	22	10	525	20	1	1,461	56	2,095	2.52
Southeastern Asia (Rest of)	8	70	80	428	15	1	41	1,405	2,048	2.46
India	15	260	63	1,301	20	2	38	146	1,846	2.22
Australia	3	8	7	27	19	0	836	165	1,066	1.28
South America (Rest of)	4	60	54	116	26	1	312	392	966	1.16
USA	72	60	143	198	28	5	97	227	831	1
Canada	7	13	14	19	8	0	56	551	669	0.81
Mexico	7	20	107	39	22	1	52	265	513	0.62
Central America	3	49	29	62	7	1	19	294	463	0.56
South Asia (Rest of)	1	45	21	315	1	1	9	27	420	0.5
Central Europe (Rest of)	9	19	25	250	10	3	15	49	380	0.46
Asia-"Stan"	2	6	5	157	11	2	179	3	364	0.44
Ukraine	2	13	7	224	22	1	6	21	297	0.36
Thailand	4	51	38	38	8	0	19	102	261	0.31
Argentina	2	28	23	8	31	0	103	53	249	0.3
Middle East	27	14	171	5	28	1	2	0	248	0.3
Western Europe (Rest of)	23	29	36	85	5	2	40	10	230	0.28
South Africa	4	17	46	38	6	0	110	0	222	0.27
Venezuela	5	6	40	2	3	0	68	76	199	0.24
Northern Africa	6	10	51	104	5	1	1	0	179	0.22
South Korea (Republic of Korea)	15	71	24	11	13	1	0	4	137	0.17
Japan	19	36	30	14	6	1	0	23	130	0.16
France	8	6	18	53	0	1	2	4	92	0.11

Region	Energy	Industry	Transport	Residential/ Domestic	Ag Waste Burning	Waste	Grasssland Fires	Forest Fires	Total	Country/US Ratio
Baltic States (Estonia, Latvia,	1	1	2	64	0	0	1	11	79	0.1
Turkey	8	9	19	15	17	0	2	0	70	0.08
North Korea (Democratic Peoples Republic)	0	13	1	28	0	0	0	16	58	0.07
Germany	11	8	21	13	0	1	1	0	56	0.07
Taiwan	5	29	12	1	0	0	0	1	46	0.06
Italy	9	5	13	8	0	1	5	3	45	0.05
United Kingdom	8	6	14	7	0	1	1	0	36	0.04
New Zealand	0	1	1	4	1	0	0	0	8	0.01
World Total	**368**	**2,249**	**1,447**	**7,746**	**696**	**47**	**10,800**	**12,372**	**35,725**	

of the residential (domestic) emissions come from cook stoves that burn biomass, dung or coal resulting in significant emissions of BC. China, India, and Africa to contribute nearly two-thirds of the total BC emissions from this source category, an issue discussed in more detail in Chapter 10.

Table 4-6 displays the global BC, OC, and OC/BC ratios for 6 major source categories. Transportation sources show the lowest OC/BC ratios, while burning categories are seen to be dominated by OC emissions and industrial sources are somewhere in the middle. All these sources also emit CO_2 and other GHGs as well as sulfur emissions that transform into SO_2, NO_x emissions that transform into nitrates and contribute to ozone, and other particles.

Figure 4-11 ranks BC emissions estimates for the 37 world regions shown in Table 4-4, highlighting the relative contribution of open biomass (grassland and forest fires) and anthropogenic sources. With this AR5 BC inventory, regions like Africa, Brazil, and Australia are dominated by open biomass burning sources whereas countries like the United States, China, and India are dominated by anthropogenic sources.

Figure 4-12 details the relative contribution of emissions for the 8 sectors in each of the 37 regions ranked in Figure 4-11. Forest fires, grassland fires, industry, and transportation are all major sources of BC depending on world region. Areas like Asia have significant emissions from industry, domestic, and transportation sectors. Africa and South America are generally dominated by open biomass burning sources. Developed regions like the Middle East, Japan, Europe, and the United States are dominated by transportation sources. In the international inventory, "nonroad" emissions are included in the industry category, whereas in the domestic inventory these emissions are counted in the mobile source category. It is not possible to determine what percentage of "industry" emissions are actually "nonroad" emissions in the AR5 inventory.

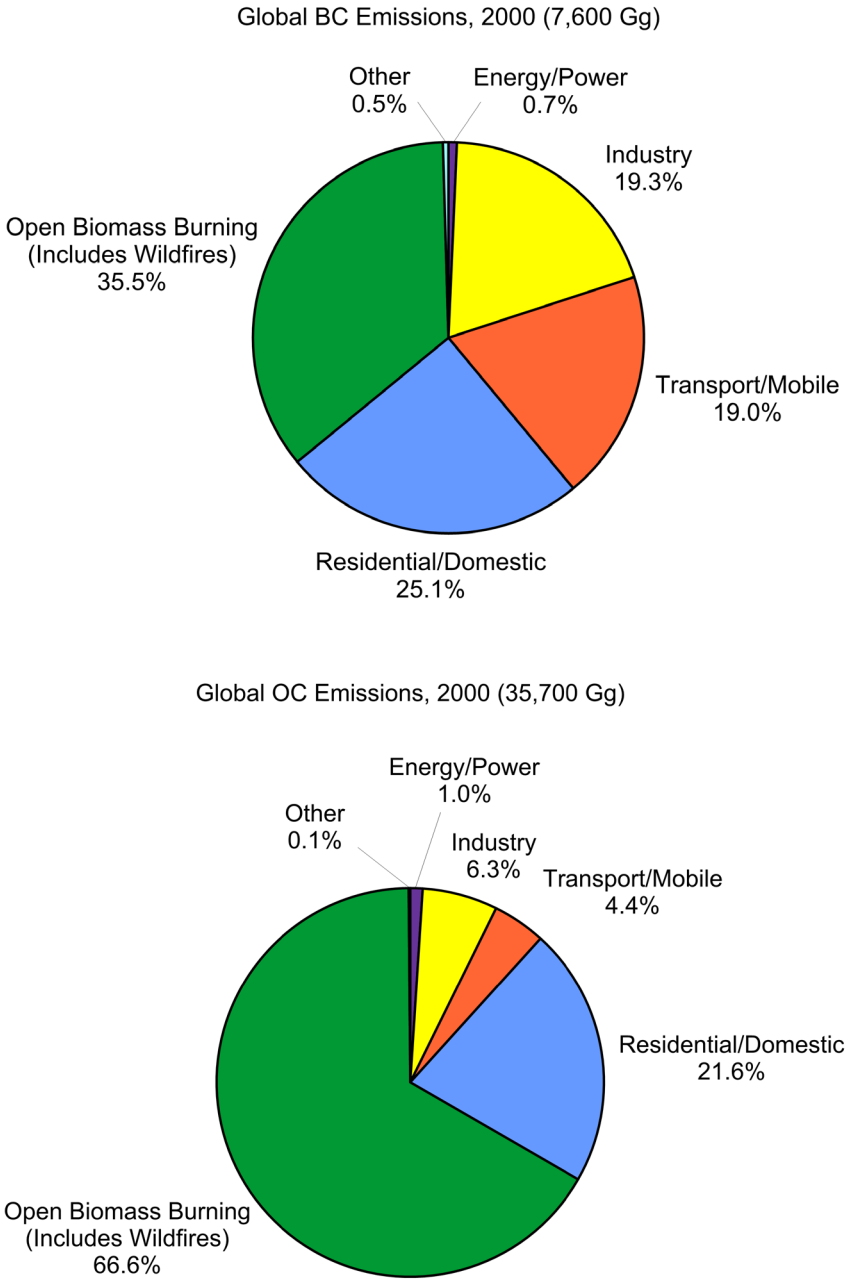

Figure 4-10. Global Distribution of BC and OC Emissions by Major Source Category. (Source: Lamarque et al., 2010)

Emissions estimates for BC and OC are generally more uncertain compared to estimates for CO_2, SO_2, or other pollutants primarily because BC is emitted by a large number of small, dispersed sources with irregular operating conditions, such as cookstoves, biomass burning, traffic, and construction equipment. Low technology-combustion (e.g.,

Table 4-6. OC/BC Ratios by Broad Source Categories. (Source: Lamarque et al., 2010)

Source Category	BC (Gg)	OC (Gg)	OC/BC
Energy/Power	54	368	7
Industry	1,497	2,249	2
Transport/Mobile	1,340	1,447	1
Domestic/Residential	1,947	7,746	4
Open Biomass Burning	2,755	23,868	9
Waste	35	47	1
Totals	**7,628**	**35,725**	**4.7**

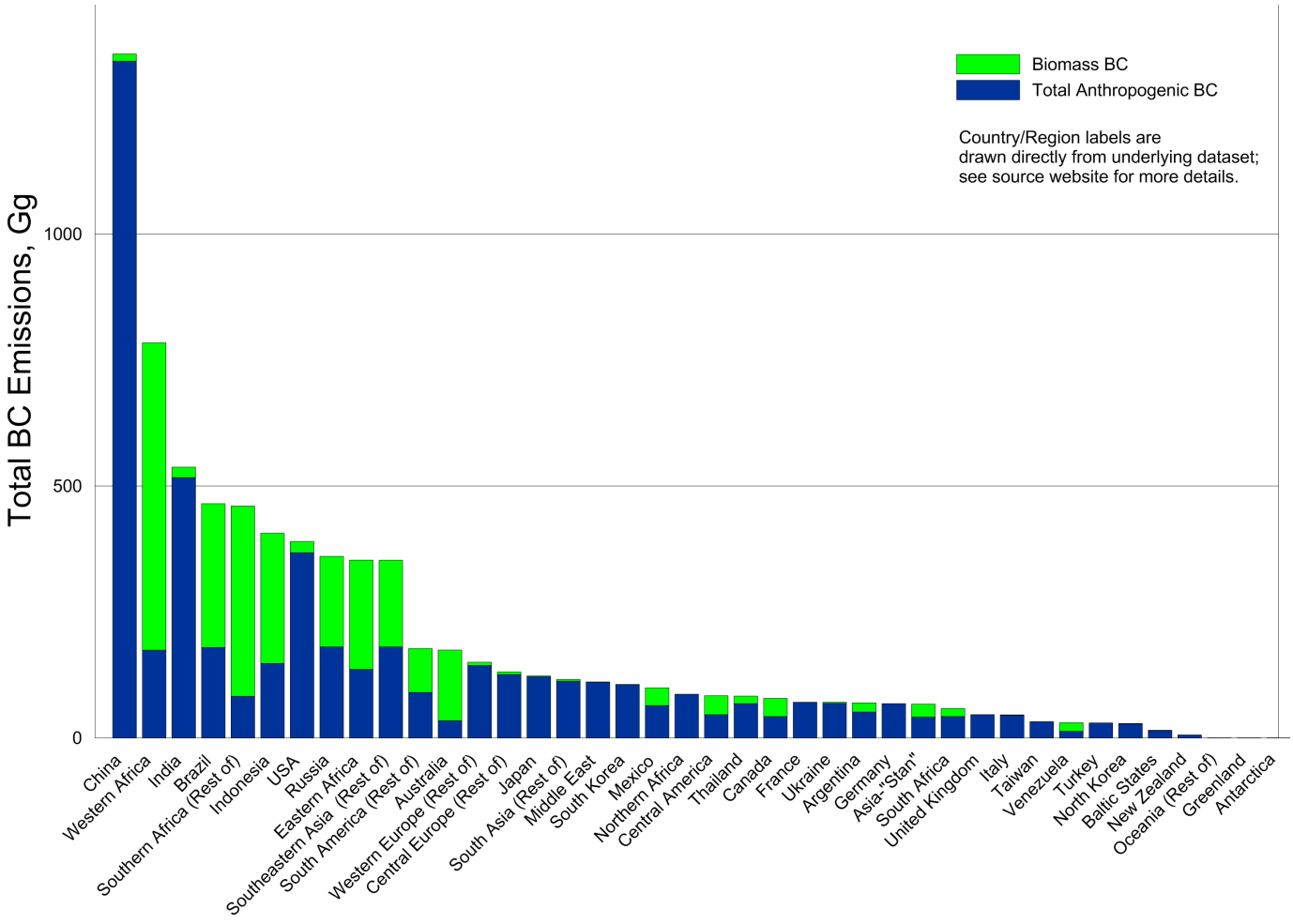

Figure 4-11. BC Emissions by World Region, 2000 (Gg). (Source: Lamarque et al., 2010, based on data from *http://acd.ucar.edu/~lamar/ipcc_ar5/bc.tar.gz*)

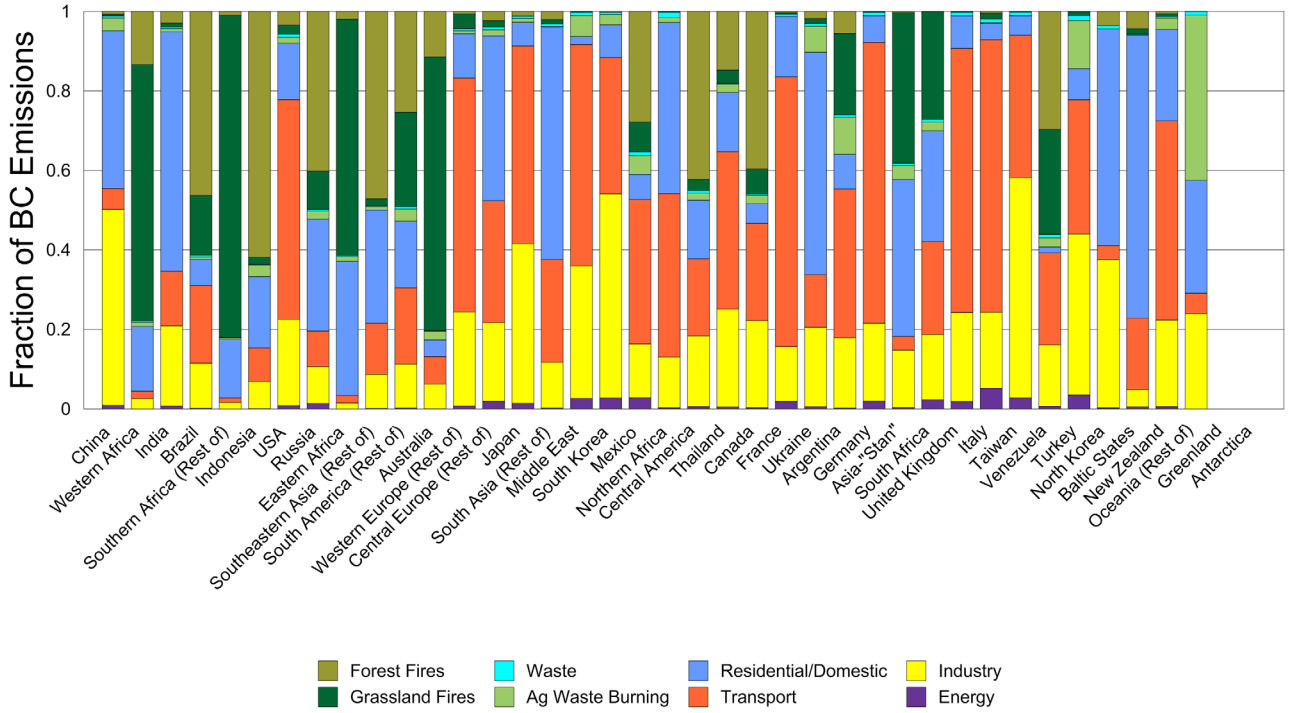

Figure 4-12. Global BC Emissions by Source Categories and Region. (Source: Lamarque et al., 2010)

"open burning") contributes greatly to both the emissions and uncertainties. There has not been a lot of work done on estimating uncertainties with BC emissions estimates. However, Bond et al. (2004) do present a bottom-up estimate of uncertainties in source strength by combining uncertainties in PM emission factors, emissions characterization, and fuel use patterns. They judge the precision of total BC emissions estimates to be within a factor of two. Advances in emissions characterizations for small residential, industrial, and mobile sources and top-down analysis combining field measurements and modeling with iterative inventory development will likely be required to reduce these uncertainties further. The general "factor of 2" in overall uncertainty estimated by Bond et al. (2004) is comparable to the range of estimates of climate forcing by BC given in the 4th IPCC assessment (IPCC, 2007).

4.4.2 Black Carbon Emissions North of the 40th Parallel

Emissions north of the 40th parallel are thought to be particularly important for BC's climate-related effects in the Arctic (Ramanathan and Carmichael, 2008; Shindell et al., 2008b). The 40th parallel north is a circle of latitude that is 40 degrees north of the Earth's equatorial plane. Globally, it crosses Europe, the Mediterranean Sea, Asia, the Pacific Ocean, North America, and the Atlantic Ocean. In the United States, the 40th parallel approximately bisects New York City in the East and San Francisco in the West, passing near Trenton, NJ, Philadelphia, PA, Columbus, OH, Indianapolis, IN, Springfield, IL Kansas City, MO, and Denver, CO. The importance of BC emissions, and especially marine shipping activities (which is a significant source contributor in the Arctic), affecting the Arctic region has been highlighted recently in several articles and reports (Arctic Council, 2009; Skeie et al., 2011). Arctic shipping emissions (which are not fully characterized in Figure 4-13) have been recently published in work on regional inventories by Corbett et al. (2010), Peters et al. (2011), and Paxian et al. (2010).

Global inventories indicate that most BC emissions, particularly from fossil fuels, occur in the Northern Hemisphere. Therefore, emissions north of 40°N latitude may be of particular concern in understanding the impacts of BC on climate. In addition, communities in proximity of the Arctic that are health receptors also stand to benefit from BC emissions reductions north of 40° latitude (these issues are dealt with in greater detail in Chapters 2, 6, and 12). Figure 4-13 presents the magnitude of global BC emissions and source contributions by latitude. Transportation is the largest source of

global BC emissions north of the 40th parallel, though open burning, residential burning, and industrial sources all contribute emissions north of 40°N in the Bond et al. inventory. These patterns have implications for assessing the contribution of source regions to snow melt in the Arctic as well as total BC-related forcing in the Northern Hemisphere.

While Figure 4-13 details the global distribution of BC emissions by sector above the 40th parallel, BC emissions from U.S. sources north of the 40th parallel are displayed in Table 4-7. About 260,000 of the 637,000 tons (41%) are estimated to be emitted in areas north of the 40th parallel. In terms of the percentage of emissions from specific source categories occurring above the 40th parallel, most categories show BC emissions contributions north of the 40th parallel that are proportionate to the number of U.S. counties in that region (about 38%). The exceptions are the Fossil Fuel Combustion and Biomass Combustion categories. "North of 40" emissions from biomass burning are seen to be 51% of the total domestic BC emissions from this source category, which is attributable to the wildfire emissions from Alaska. However, as discussed earlier in this chapter, Alaskan wildfire activity is highly variable from year to year, so these emissions may vary. (Furthermore, mitigating wildfire emissions presents particular challenges, as discussed in Chapter 11.) BC emissions from fossil fuel combustion north of the 40th parallel represent only a small percentage (6%) of all emissions across the United States for this source category.

In terms of the contribution of specific source categories to total U.S. BC emissions (from all

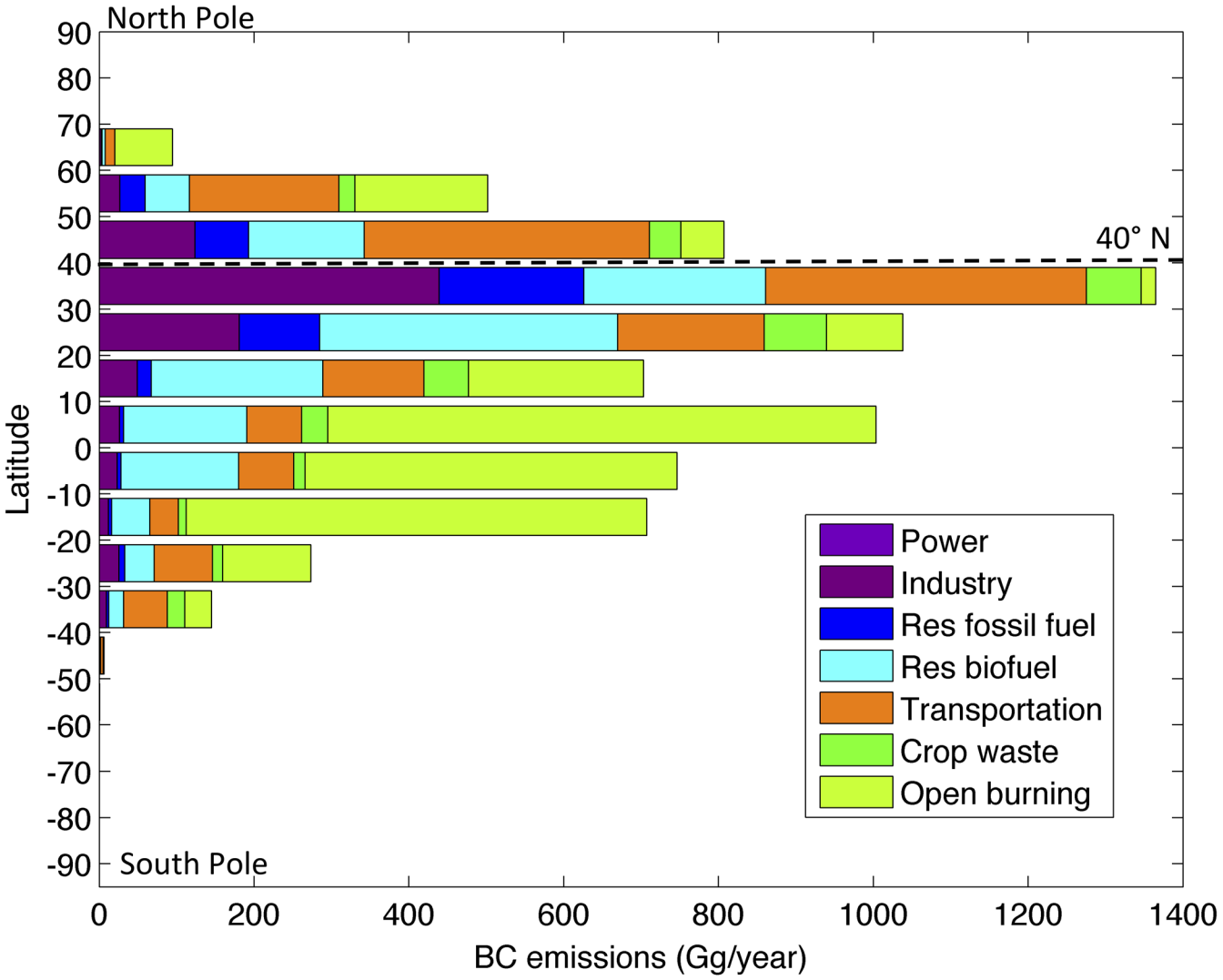

Figure 4-13. Geographical Distribution of Global BC Emissions by Latitude. (Source: Bond, 2008)

Table 4-7. A Comparison of BC Emissions Nationally to Those from Sources "North of 40th Parallel" in 2005 (short tons). (Source: U.S. EPA, 2005a)

Source	Total US BC Emissions	BC Emissions Estimated North of the 40th Parallel	Percent of BC Emissions From This Source Category Emitted North of the 40th Parallel	Percent of TOTAL BC Emitted North of the 40th Parallel
Biomass Combustion	250,499	128,501	51%	49%
Fossil Fuel Combustion	43,049	2,794	6%	1%
Fugitive Dust Sources	1,609	483	30%	0%
Industrial Sources	6,085	1,574	26%	1%
Mobile Sources	333,405	125,784	38%	48%
Other Minor Sources	2,525	755	30%	0%
Totals/averages	**637,172**	**259,891**	**41%**	

categories) occurring above the 40th parallel, it is important to note that biomass burning and mobile sources are by far the dominant contributors. Together, these sources make up approximately 97% of the U.S. BC emissions estimated to occur north of the 40th parallel. The contribution from mobile sources to total U.S. BC emissions north of the 40th parallel is similar (48%) to the contribution of mobile sources to total BC emissions nationally (52%), while biomass combustion contributes 49% of total U.S. BC emissions north of the 40th parallel (compared to 35% of total BC emissions nationally). Again, this reflects the heavy influence of Alaskan wildfire emissions.

4.4.3 Alternative Estimates of Global and Regional Emissions

In addition to the widely used Lamarque/Bond inventory discussed above, there are other global BC and OC emissions inventories compiled by other researchers. Seven other global BC and OC inventories are available in the published literature (Cooke and Wilson, 1996; Cofala et al., 2007; Penner et al., 1993; Junker and Liousse, 2008). The total BC emissions estimated in these inventories fall in the "factor of 2" error range estimated in Bond's BC inventory, which signals that these estimates are generally consistent with the estimates presented above. Most of these alternative emissions are developed using "bottom-up" approaches, similar to that used by Bond et al. (2004) and Streets et al. (2004). These are summarized and discussed further in Appendix 2. The alternative emissions inventories do not provide as much detail or as comprehensive an explanation of uncertainty in the estimates as the Bond inventories employed in this chapter.

An advantage of global inventories is that the emissions estimates are compiled using consistent definitions and methods across all regions. The global inventories, however, do not necessarily employ region or country specific emission factors, activity levels, and other surrogates. Regional emissions inventories, constructed for specific regions, nations, or local areas, often make use of more accurate data from local and government sources. This may allow for improved BC emissions estimates relative to data drawn from models or global energy databases. Regional inventories are more likely to account for differences in the composition of the fuel burned, the diversity of technologies (especially in developing countries), and the importance of smaller sources that can often be overlooked in global inventories. Some of these regional inventories are based on "top-down" type approaches while others are based on the traditional "bottom-up" approaches described earlier. Reconciling the global inventories with regional inventories is complicated by differences in methods used for each inventory. Good regional inventories, however, may still be used to evaluate the global estimates, and can be used to inform future versions of those global inventories.

Most of the regional BC inventory efforts to date have focused on the Asian sub-region (Zhang et al., 2007; Cao et al., 2006; Sahu et al., 2008; Streets et al., 2003a; 2003b; Ohara et al., 2007; Dickerson et al., 2002; Mayol-Bracero et al., 2002; Reddy and Venkataraman, 2002a; 2002b; Parashar et al., 2005) likely due to high emissions of BC and OC from diverse sources there. There are fewer regional BC inventories available for European countries. In general, global emissions inventories have to be used to estimate European BC emissions. Recent

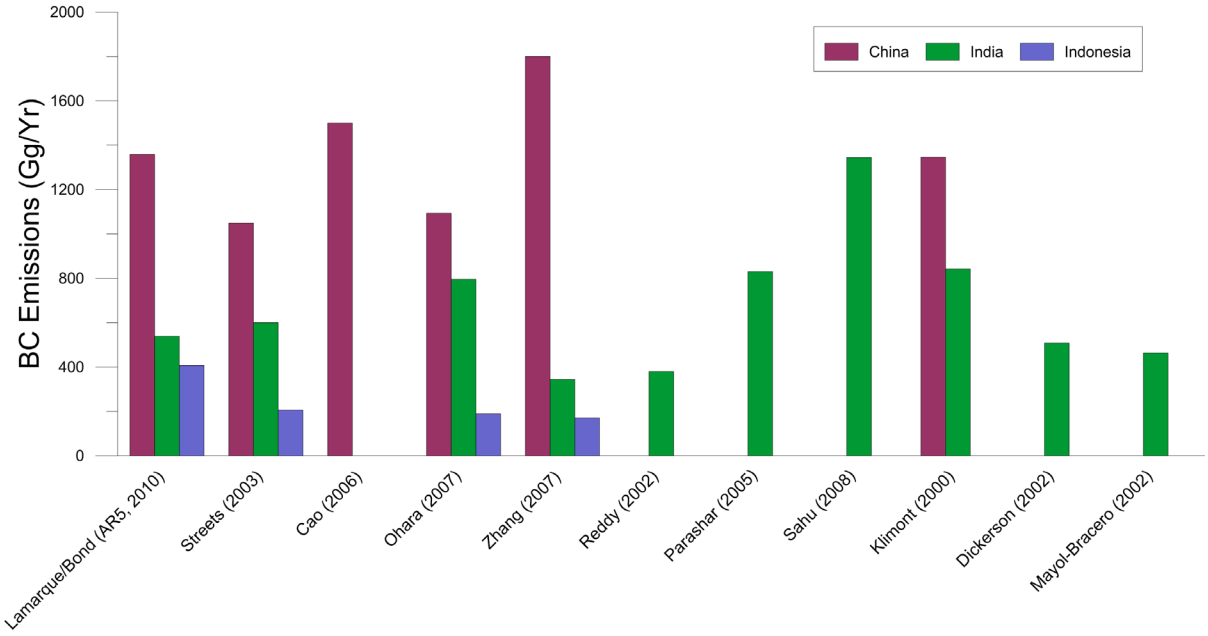

Figure 4-14. Comparison of Regional Inventories for China, India, and Indonesia with AR5 Estimates. (Source: U.S. EPA)

work by the Arctic Council to estimate BC and OC emissions for Arctic nations may provide useful information on regional inventories in those nations. A full list of available regional inventories, along with additional details about the methods used, is available in Appendix 2.

Figure 4-14 compares some of the different regional BC emissions estimates for China, India, and Indonesia to the estimates from AR5 inventories. In general, even though the publication year of the study (indicated on x-axis label in Figure 4-14) is different in most cases, these inventories are seen to be fairly consistent with one another, and also with the Bond global inventory. The range of emissions for a country from these various inventories also gives an indication of the amount of uncertainty in BC emissions estimates for a given region. All of the regional estimates are within the error bounds estimated by Bond et al. (2004) for BC emissions. Recently, EPA's Office of International and Tribal Affairs (OITA) commissioned a study (U.S. EPA, 2011b) to look at reducing BC emissions from various sectors in South Asia. Some of the studies highlighted in Figure 4-14 are discussed in more detail in Appendix A of that report, one of the interesting things the study points out is that BC emissions vary according to the season of the year for certain sectors in South Asia. As a result, emissions tend to peak during the dry season months preceding the monsoon in South Asia.

In addition, for future work to improve the global estimates, these regional estimates can be used to "bound" estimates for a given world region or country. Finally, it is important for countries to begin developing regional inventories of BC and OC, to better identify sources and their BC emissions, and to supplement global inventories that sometimes rely on "default" type information to develop regional estimates. Having more accurate "localized" inventories will enable better and more effectively designed mitigation strategies for specific sources in specific world regions.

4.4.4 Inventory Comparisons for U.S. Black Carbon Emissions

Table 4-8 compares the U.S. portion of the 2000 global AR5-based BC and OC emissions estimates of Lamarque/Bond et al. (in green) to the EPA's BC estimates for 2002/2005 (in orange). U.S. emissions from the global inventory are aggregated to the highest level of source category detail possible to facilitate comparisons with EPA-based BC

Table 4-8. Comparison of BC and OC Emissions (in Gg) for the United States between AR5 Global Inventories and EPA Inventories. (Source: Lamarque et al., 2010)

BC Emissions (Gg) in AR5 and EPA Inventories

AR5 Source Description	BC	EPA Source Description	BC	EPA Estimates High By
Energy	3	Energy/Power	39	1200%
Industry	85	Industrial	6	-93%
Transport	216	Mobile Sources	302	40%
Residential	55	Residential	21	-62%
Agricultural Waste Burning	6	Agricultural Burns	13	117%
Waste	3			
Grassland Fires	9	Prescribed Burns	53	489%
Forest Fires	13	Wildfires	138	962%
Totals:	**390**		**572**	**47%**

OC Emissions (Gg) in AR5 and EPA Inventories

AR5 Source Description	OC	EPA Source Description	OC	EPA Estimates High By
Energy	72	Energy/Power	59	-18%
Industry	60	Industrial	15	-75%
Transport	143	Mobile Sources	186	30%
Residential	198	Residential	185	-6%
Agricultural Waste Burning	28	Agricultural Burns	46	64%
Waste	5			
Grassland Fires	97	Prescribed Burns	244	151%
Forest Fires	227	Wildfires	670	195%
Totals:	**830**		**1,405**	**69%**

estimates.[14] The degree of difference between the EPA inventory and the AR5 inventory for U.S. emissions is depicted as a percentage in the light blue column.

Total BC emissions for the United States are estimated to be about 390 Gg in the AR5 inventory, and about 572 Gg in the EPA inventories.[15] Most of this approximately 50% difference is driven by EPA estimates for open burning and (to a lesser extent) for mobile sources in the United States that are higher than those from the global inventories. As discussed previously, wildfire emissions can vary greatly from year to year and depend substantially on both fire reporting systems used and emissions calculation method (Larkin et al., 2009; 2010). This may explain some of the difference between the

[14] In general, aggregating emissions from different inventories to this level of broad source categorization introduces uncertainties since an accurate matching of individual source categories to these larger source categories is not always possible. The specific source types included in the more broad categories in the AR5 inventories (and used in Table 4-8) are unclear and details were not available for this Report. More work is needed in comparing region-specific inventories from global estimates to regionally developed inventories, and especially to better understand the sources that make up the larger sectors that are generally depicted in reports and publications.

[15] EPA's estimate of the domestic BC emissions in Table 4-8 (572 Gg) is a bit smaller than the total BC emissions estimate shown earlier in this chapter (578 Gg). This difference stems from the fact that most of the sources in the "Other" mega source category from the U.S. inventory were not included here. In addition, note that while an emissions estimate (albeit small) for a "Waste" category is provided in the global inventories, no such estimate was included in the U.S. EPA derived inventory.

estimates for open burning as the AR5 estimates are based on the year 2000 and the EPA estimates on the year 2002 and different reporting systems and fuel loading/consumption characteristics are used. Also, EPA estimates include all nonroad and on-road emissions in the transportation source category, while global inventories group emissions from some of the smaller nonroad sources into the "Industry" category. This could account for global inventory estimates of U.S. emissions being lower for "transport" and higher for "industry" compared to the EPA estimates. In the case of OC emissions, Table 4-8 shows that the AR5 total is about 830 Gg while the EPA estimates are seen to be about 1,405 Gg, a difference of about 69%. As with BC, most of this discrepancy stems from fire emissions that EPA estimated to result in more OC than do the AR5 estimates for the United States. It is likely that fire emissions (both OC and BC) from many countries are under-estimated due to the methods used to estimate fire emissions in global inventories including an insufficient accounting for emissions from smaller fires.

The comparison of BC emissions from the most often used global estimates by Lamarque/Bond et al. to BC inventories developed by EPA reveal important differences that necessitate further investigation. A key focus of any future examination is how these differences may influence the estimates of regional effects from global climate models. However, as noted in Chapter 2, emissions uncertainties are not thought to be as important as other factors in determining climate impacts from model output (Koch and Del Genio, 2010). In addition to better understanding the role of uncertainty in emissions estimates on impacts simulated by models, more work is needed to better understand the source make-up of sectors with large differences between the two inventories (e.g., biomass combustion sources, mobile sources, and some parts of the residential sectors). In addition, it is necessary to clarify the characterization of the uncertainties associated with global BC and OC emissions (and "the factor of 2" often discussed) estimated by Bond et al. Development of uncertainty in emissions estimates by sector for the U.S. and global inventories should be a focus of future work.

4.5 Long-Range Transport of Emissions

Aerosols emitted in a particular region can be transported long distances through the atmosphere to other regions of the globe. Therefore, BC emitted in one place can affect radiative forcing in other locations downwind. Furthermore, the climate impacts of BC, such as effects on temperature and precipitation, do not necessarily occur where the radiative forcing occurs and may occur downwind of the source region (Shindell et al., 2008b; TF HTAP, 2010). The relationships between where pollutants are emitted and where their impacts are experienced are often characterized as "source-receptor" relationships. Emissions in a source region are transported, or lead to formation of additional aerosols that then are transported, and eventually deposit or affect the receptor regions downwind. Long-range or intercontinental transport of aerosols may occur in the planetary boundary layer (PBL), which is the layer of the atmosphere that is in contact with the earth's surface, or in the free troposphere, which is the layer of the atmosphere just above the PBL but below the stratosphere. Aerosols that have been lofted above the boundary layer into the free troposphere can be transported long distances due to the relatively small amount of precipitation and high wind speeds. In the mid-latitudes of the Northern Hemisphere, long-range transport is largely from west to east, due to the prevailing winds. However, different transport patterns are dominant in other parts of the world.

The Task Force on Hemispheric Transport of Air Pollution (TF HTAP) organized under the Convention on Long-range Transboundary Air Pollution conducted a multi-model assessment of long-range transport of aerosols and other pollutants from four main source regions in the Northern Hemisphere approximating the populated regions of North America, Europe, South Asia, and East Asia (TF HTAP, 2010). The models included in the study produced widely varying estimates of the absolute amount of intercontinental transport of aerosols. Most of the diversity in model estimates appears to be due to differences in the representation of physical and chemical transformations that aerosols undergo in the atmosphere, which leads to differences in the estimated atmospheric lifetime of aerosols. Uncertainties in emissions estimates and atmospheric transport algorithms also contribute to the diversity of estimates. A systematic comparison between the TF HTAP ensemble estimates and observations in the mid-latitudes has not been conducted.

Although the absolute estimates in the TF HTAP ensemble are quite different, the relative contributions of the four continental source regions to concentrations or deposition downwind are more consistent. In the North American region, it was estimated from the ensemble of simulations that about 80% (±25%) of the BC deposited in North America is from anthropogenic sources in North America. Open biomass burning, largely forest

fires (wildfires), across North and Central America contribute about 12% (±17%). Other emissions sources from outside North America contribute about 8% (±17%) of the BC deposited within the North American study region.

The TF HTAP multi-model study also examined the impact of intercontinental transport on total atmospheric column concentrations, aerosol optical depth, and aerosol radiative forcing. The TF HTAP concluded that intercontinental transport associated with anthropogenic sources of BC (not including open biomass burning) accounted for roughly 30% of the aerosol optical depth and direct aerosol radiative forcing over North America. Similarly, anthropogenic BC emissions from North America are likely to contribute 10-30% of the BC radiative forcing over other regions of the Northern Hemisphere. This ensemble study would suggest that long-range transport of BC is a minor contributor to surface concentrations over North America, but a major contributor to the radiative forcing and regional climate impacts of BC. It is worth noting that the results were calculated using rather coarse global-scale models and variations within the North American region were not investigated.

The results of the TF HTAP multi-model experiments are consistent with previous modeling results that showed that sources outside North America make a relatively small contribution to surface aerosol levels in North America (Chin et al., 2007; Koch et al., 2007b) and that intercontinental transport of BC emissions, particularly from South and East Asia, is more important for surface concentrations or deposition at high altitudes (Hadley et al., 2007) and for total column loadings and climate impacts (Reddy and Boucher, 2007; Koch et al., 2007b).

In recent work, Kopacz et al. (2011) estimated the contribution of BC emissions sources to BC concentrations and deposition in the Himalayas and Tibetan Plateau and the associated direct and snow-albedo radiative forcing. They conclude that emissions from northern India and central China and from western and central China contribute most of the BC in the Himalayas and Tibetan Plateau, respectively, although the contributions of different locations vary with season. However, they also show that the Himalayas and Tibetan Plateau region can receive significant contributions from very distant sources including biomass burning in Africa and fossil fuel combustion in the Middle East. They estimate that the snow-albedo effect of BC deposition on snow in the region results in a warming influence that is an order of magnitude larger than the direct radiative forcing influence.

Given the paucity of anthropogenic sources of BC in the Arctic, a large fraction of the climatic impact of BC in the Arctic can be attributed to long-range transport. Shindell et al. (2008b) examined the results of the TF HTAP multi-model experiments for insights about transport to the Arctic. Comparing to observations of BC at Barrow, Alaska, and Alert, Canada, all of the models appeared to underestimate the transport of BC to the Arctic. Consistent with the findings for the source-receptor relationships at mid-latitudes, they found that the models varied widely in terms of the absolute estimates of the contribution of different source regions, but were similar in their estimates of the relative contributions. The ensemble results suggest that European emissions are the largest contributors to surface BC in the Arctic (due to the high latitude, and therefore Arctic proximity, of many European sources), while East Asia is the largest contributor to BC in the upper troposphere (Figure 4-15) (Shindell et al., 2008b). Additional source apportionment analysis under the TF HTAP (2010) concluded that anthropogenic emissions from Europe and open biomass burning emissions from Eurasia both contributed about 35% of the surface BC in the Arctic. Anthropogenic emissions from the North

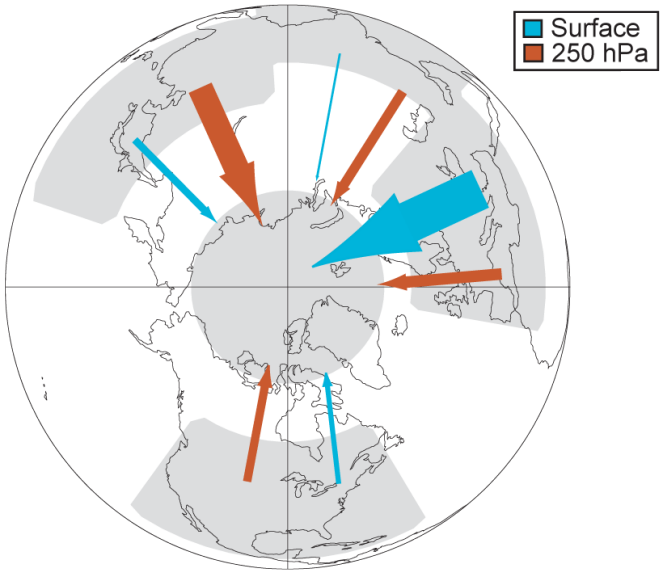

Figure 4-15. Relative Importance of Different Regions to Annual Mean Arctic BC Concentrations at the Surface and in the Upper Troposphere (250 hPa). Values are calculated from simulations of the response to 20% reduction in anthropogenic emissions of precursors from each region (using NO_x for ozone). Arrow width is proportional to the multi-model mean percentage contribution from each region (shaded) to the total from these four source regions. (Source: Shindell et al., 2008b)

American study region, not including open biomass burning, accounted for an average of 5% of surface BC in the Arctic region, with model estimates spanning the range from 2% to 10% (TF HTAP, 2010). However, unlike the rest of the Arctic, deposition of BC in Greenland, location of the second-largest ice sheet in the world, is most sensitive to North American emissions (Shindell et al., 2008b).

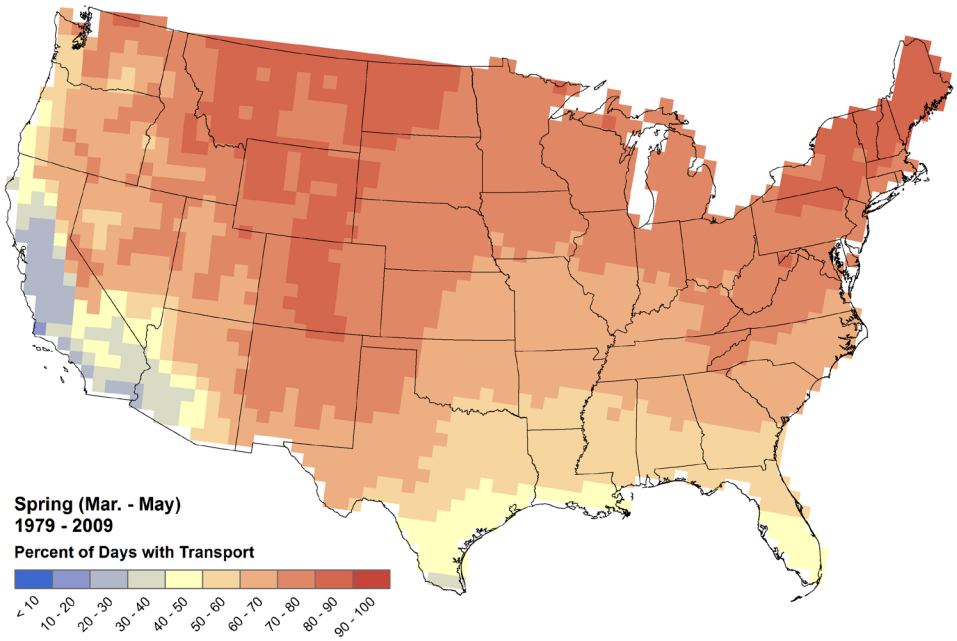

Figure 4-16. Potential for Transport of U.S. Emissions to the Arctic based on the percentage of spring days (March through May) in which seven-day forward trajectories initiated within the boundary layer (below 2000m) reached the Arctic Circle. These percentages are based on 31 years of trajectories using meteorological data from 1979-2009. (Source: USDA Joint Fire Science Program)

In addition to the TF HTAP approach of largely using grid-based models, trajectory-based models have also been employed to quantify transport to the Arctic. These models show a much stronger influence of sources in Northern Eurasian locations to Arctic surface concentrations and deposition, and much less influence from more distant sources. The exception is for high altitude sites in Greenland, which may be influenced by very different sources than the rest of the Arctic (Hirdman et al., 2010).

The contribution of both open biomass burning and fossil fuel combustion to BC deposition in the Arctic has been confirmed by detailed chemical analysis of surface snow and ice cores. However, the observational evidence would suggest that open biomass burning, including crop burning, is the dominant source of BC deposition in the Arctic (McConnell et al., 2007; Hegg et al., 2010; 2009). The relative contribution of different source types and locations, however, varies significantly across receptor locations and seasons.

Within the United States, the potential for transport of domestic BC emissions to the Arctic is known to vary by location and season. Given its proximity to the Arctic, BC emissions sources in Alaska are likely to have an impact on the Arctic, depending on the synoptic weather conditions. For emissions sources in the contiguous United States, recent trajectory modeling work by the Joint Fire Science Program (DeWinter et al., 2011; Larkin et al., 2011) has shown that the probability of emissions impacting the Arctic is critically dependent on the specific injection height into the atmosphere and the specific synoptic weather patterns prevalent at the time. Seven day forward trajectories were computed for a 31 year period (1979-2009) using synoptic weather patterns starting at a number of injection heights for each location within the contiguous United States. Figure 4-16 displays the percentage of spring days (March-May) where any of the 7-day forward trajectory releases below 2000m reached the Arctic Circle. This analysis suggests that the potential for springtime transport of BC ground-level emissions from the contiguous United States to the Arctic can be significant. Over the southern portion of the United States, the potential for transport to the Arctic is frequent (40-60%), but a significant number of days without transport remain. For locations in the northern part of the United States and other higher-altitude locations, the analysis indicated that the potential for transport trajectories to the Arctic is very common (> 70%). However, even in areas which show a large seasonal and climatological potential for transport, it is possible to identify multi-day periods where transport to the Arctic is limited. The dependency on source location and synoptic weather conditions may have implications for understanding source apportionment and for

implementing mitigation strategies. Tools are being developed to enable the use of daily predicted transport potential in mitigation strategies.

4.6 Historical Trends in Black Carbon Emissions

4.6.1 U.S. Black Carbon Emissions Trends

Historic trends and future projections of BC emissions provide an indication of the relative importance of different sectors over time and can help focus future mitigation efforts. Establishing emissions trends requires the use of a consistent estimation method. Most domestic inventories discussed earlier in this chapter are derived from methods that have changed as measurement and models have improved. As a result, care must be taken in interpreting trends of over time. However, it is possible to observe large scale changes. Specifically, the data show that U.S. emissions of BC increased steadily from the mid-1800s through 1920, and then declined over the next 8 decades. This is likely attributable to changes in fuel use from coal to cleaner fuels, more efficient combustion of coal, and implementation of PM controls. In more recent years, EPA's introduction of the NAAQS for fine particles in 1997 and strengthening of that NAAQS in 2006 necessitated $PM_{2.5}$ reductions that likely contributed to BC emissions reductions as well. In addition, since 1990, due to regulations on PM emissions from mobile sources, there have been substantial reductions in BC emissions from those sources.

Since mobile source emissions are modeled, a time series of BC emissions can be generated more easily for this source category than for other U.S. source categories. Mobile sources have experienced a 32% reduction in BC, a 51% reduction in OC, and a 36% reduction in $PM_{2.5}$ emissions from 1990 - 2005. From 1990 to 2005, BC emissions decreased by 79%, 30%, and 25% for on-road gasoline, on-road diesel, and nonroad diesel sources, respectively. Continued reductions are expected for mobile sources in the next two decades, as discussed further in Chapter 8. BC emissions for nonroad gasoline sources, though extremely small, did not change from 1990 to 2005.

BC emissions trends for the other major source categories (open biomass burning, industry, and energy/power) are difficult to estimate due to lack of data and inconsistent measurements and methods over time. The methods used to estimate emissions from 1990 to 2008 have changed significantly, as has the way $PM_{2.5}$ estimates are used to derive BC emissions estimates. There are no BC estimates available for any non-mobile source categories for the year 1990. From 1990 to about 1998 there was about a 30% reduction in direct $PM_{2.5}$ emissions from EGUs and other power-generation sources due to controls on direct $PM_{2.5}$. It is expected that some of these reductions in direct $PM_{2.5}$ led to decreases in emissions of BC, but this is difficult to verify without consistent speciation data for the entire time period. In 1999, there was a major change in the methods used estimate $PM_{2.5}$ emissions. Based on these new methods, from 1999 to 2008 an additional 21% reduction in direct $PM_{2.5}$ is seen from this source category. In contrast, direct $PM_{2.5}$ emissions from industrial sources are estimated to have declined only 6% during the entire 1990-2008 period (U.S. EPA, 2010i).

Long-term trends in emissions from biomass burning categories (wildfires, prescribed burns, and agriculture burns) are not available due to significant year-to-year changes in the methods used to estimate emissions. For that reason, in the modeling assessments "average fires" are used to represent emissions from this source category. However, qualitative estimates of annual wildfire frequency/activity as well as future wildfire activity in the United States are available and suggest upward trends. Global climate change is expected to make the increased activity even greater with more fuel availability and drier, more combustion-friendly conditions.

4.6.2 Global Black Carbon Emissions Trends

There are a number of studies available which have looked explicitly at global BC emissions trends over time (e.g., Bond et al., 2007; Ito and Penner, 2005; Novakov et al., 2003). Figure 4-17 (Bond et al., 2007) shows the growth in global BC emissions from key source categories (excluding biomass burning) during the period between 1850 and 2000. The figure shows that emissions of BC have increased almost linearly, totaling about 1000 Gg (approximately 1.1 million tons) in 1850, 2200 Gg (approximately 2.4 million tons) in 1900, 3000 Gg (approximately 3.3 million tons) in 1950, and 4400 Gg (approximately 4.8 million tons) in 2000. The slower growth between 1900 and 1950 may be due to economic circumstances and also the introduction of cleaner technology, especially in developed countries. OC shows a similar pattern of linear growth that is slightly slower in the mid-1900s.

Figure 4-18 relates BC emissions trends from Bond et al. (2007) to earlier work done by Ito and Penner (2005), and by Novakov et al. (2003).[16] Ito and

[16] Novakov et al. looked at BC from fossil fuel combustion only.

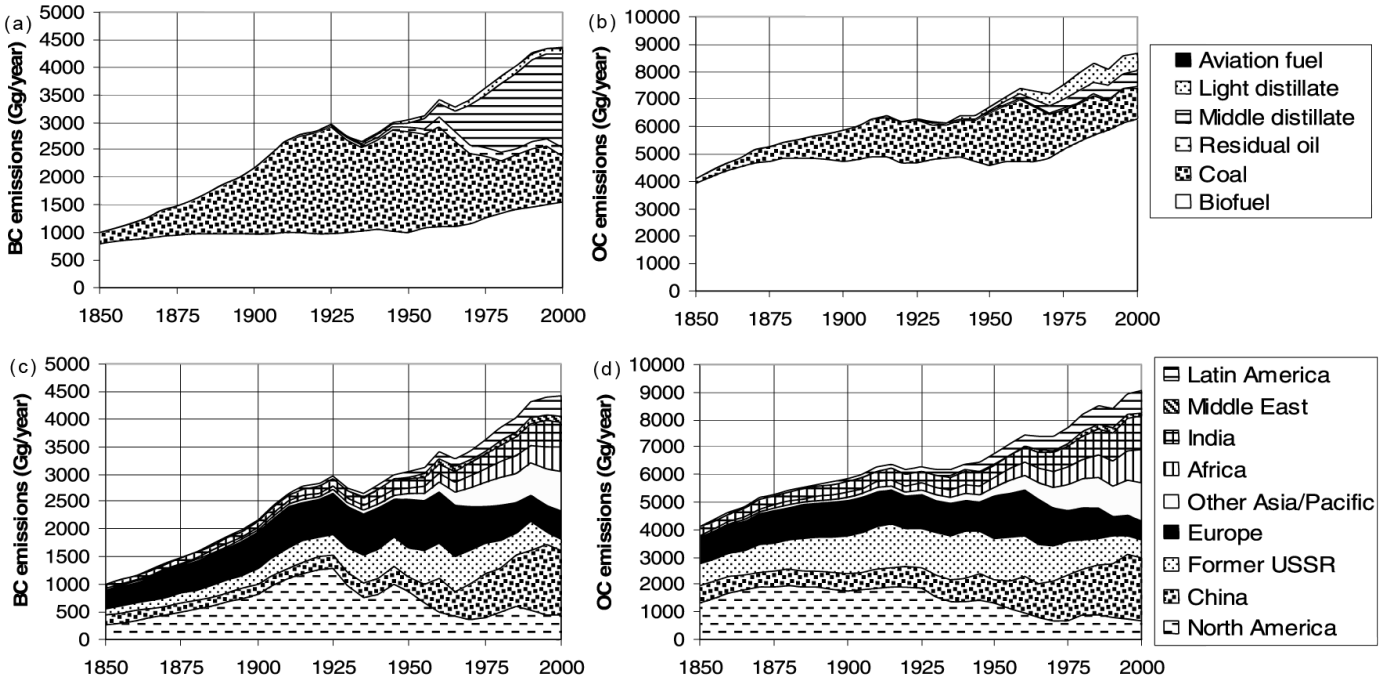

Figure 4-17. Historical Growth in Emissions of BC (Panels a, c) and OC (Panels b, d), Segregated by Fuel (Panels a, b) and World Region (Panels c, d). (Source: Bond et al., 2007)

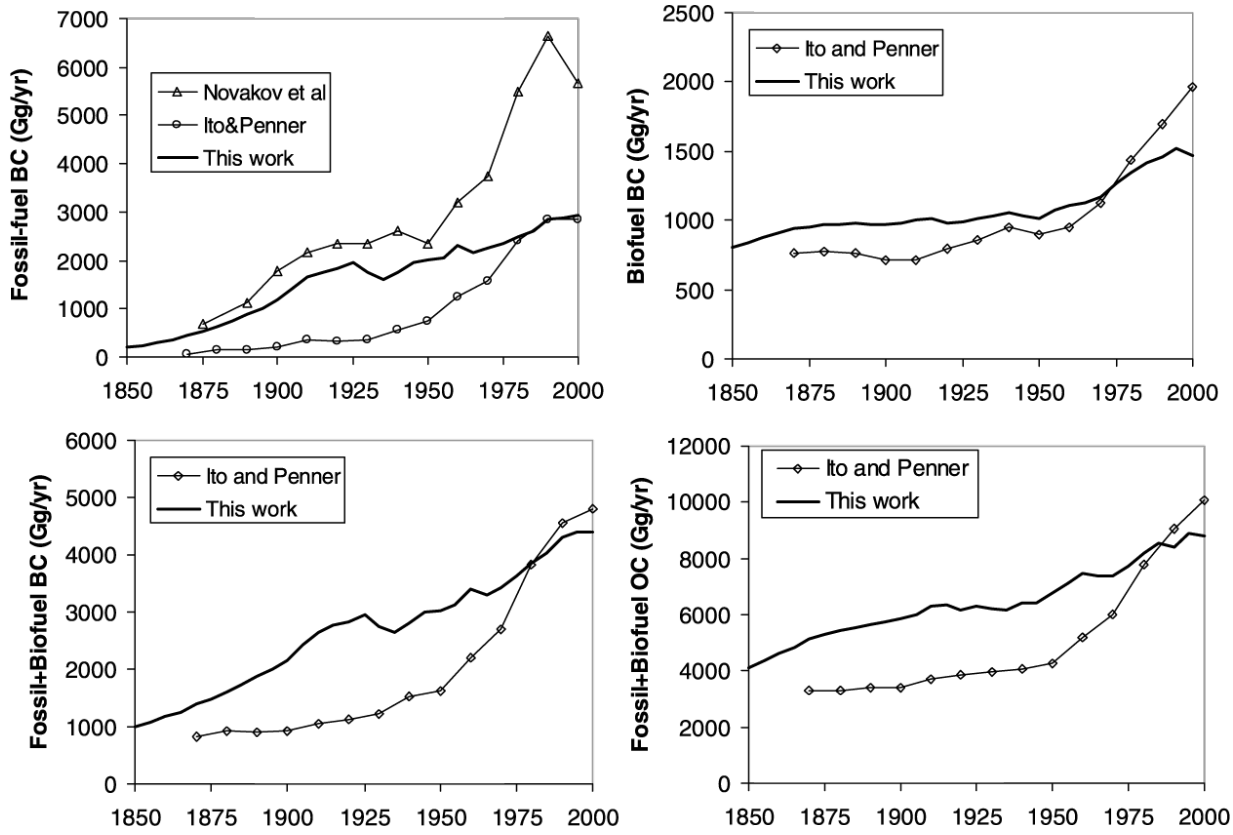

Figure 4-18. Historical Reconstruction of Global Emissions Trends. Comparison of Bond et al. (2007) ("this work") with Previous Studies.

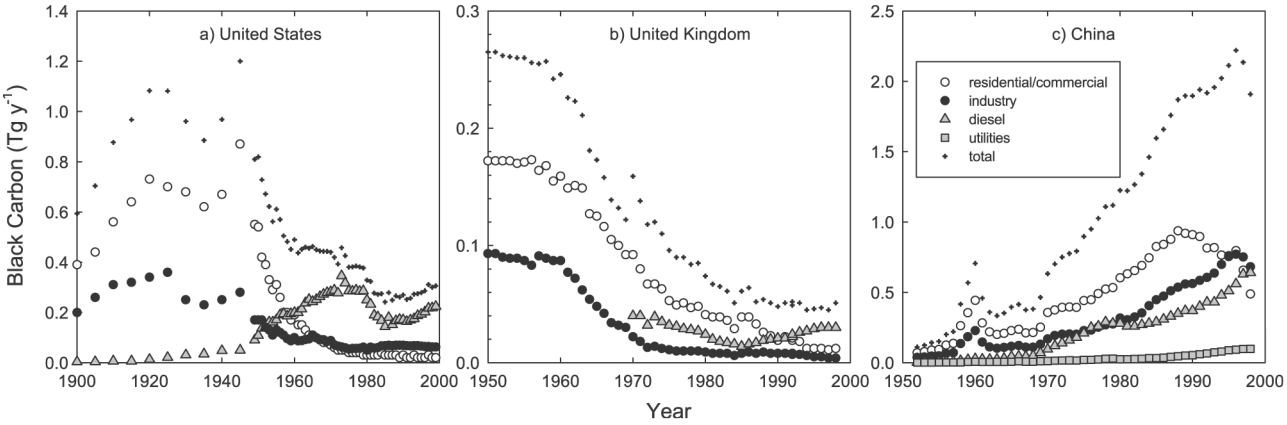

Figure 4-19. BC Emissions (Tg /y) in the United States, United Kingdom, and China (Novakov et al., 2003). BC emissions are estimated from annual consumption data for the principal BC producing fossil fuels and BC emission factors disaggregated by utilization sector. BC from biofuels and open biomass burning are not included.

Penner show a very similar trend and magnitude in BC emissions from biofuel, but the magnitude of fossil-fuel BC emissions is much lower. In the late 1900s, Bond et al.'s biofuel emissions increase less (about 30% between 1960 and 2000 vs. 100% for Ito and Penner). By contrast, Novakov et al. estimated higher fossil-fuel BC emissions than Bond et al., in the early 1900s. Novakov et al.'s work was based on total BC aerosol, while Bond et al. and Ito and Penner's work focused on fractions of PM less than 1 micron in diameter. Novakov et al. shows flat BC emissions between about 1910 and 1950, similar to Bond et al. (2007).

The greatest difference between the more recent Bond et al. (2007) work and the earlier Ito and Penner and Novakov et al. work is the more gradual transition in the latter half of the 20th century. Both of the earlier studies considered the introduction of cleaner diesels and some changes in sectoral divisions. Bond et al. modeled shifts to cleaner burning through increases in consumption in cleaner sectors. Bond et al. indicate the shift to cleaner burning coal explicitly for the first time, reducing BC emissions from this sector. It is likely that the difference between the three studies is largely attributable to the choice of emission factors, which entails some implicit assumptions about technology choices.

Figure 4-19 shows the estimated BC emissions trends for the U.K., United States, and China (Novakov et al., 2003). According to these data, emissions from the United States peaked in 1920, while Europe peaked in 1950 and has declined about 90%. Total global emissions of BC, however, have been steadily increasing since 1875 (Novakov et al., 2003). Presently, global BC emissions total approximately 8.4 million tons. Almost all of the increase in recent decades is from developing countries in Asia, Latin America, and Africa. China and India contribute nearly 25% of global BC emissions.

Together, these emissions trends studies and other works suggest that developed countries dominated global BC emissions until the adoption of pollution control technologies and fuel-use shifts began to slow growth and eventually to result in significant reductions after mid-century (Bachmann, 2007; 2009; Ramanathan et al., 2007). Available data suggest that BC emissions from developed countries have declined substantially over the past several decades, while emissions from developing countries have been growing. Today, the majority of BC emissions are from developing countries (Bond et al., 2007) and this trend is expected to increase (Jacobson and Streets, 2009; Kupiainen and Klimont, 2007).