Methods for Improving Global Inventories of Black Carbon and Organic Carbon Particulates

William Battye and Katherine Boyer
EC/R Incorporated
1129 Weaver Dairy Road
Chapel Hill, NC 27514
battye.bill@ecrweb.com
boyer.kathy@ecrweb.com

Thompson G. Pace, D205-01
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711
pace.tom@epa.gov

ABSTRACT

Black carbon and organic carbon particles emitted from combustion sources interact with sunlight and can impact climate change processes. These particles also contribute to visibility impairment and to elevated ambient levels of fine particulate matter ($PM_{2.5}$). For black carbon in particular, measures to reduce climate-forcing emissions often would have collateral benefits by reducing emissions of health-related pollutants, and vice versa. A better characterization of worldwide emissions of climate forcing and health-related pollutants is needed to improve the understanding of overlapping benefits for emission reduction strategies both in the U.S. and abroad. The improved characterization of emissions will help in two ways: by quantifying the most efficient strategies for improving both global warming and health-related problems, and by identifying sources that are under-reported or missing from different emissions inventories.

The purpose of the current research is to identify tools that can be used to improve emissions inventories for black carbon and organic carbon particles in the U.S. and abroad. Emission factors and tools used in current inventories for these pollutants are reviewed, and factors are compiled and developed for emission source categories that are not adequately covered in current inventories.

INTRODUCTION

Emissions inventories for climate change studies have focused primarily on greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and various halogenated compounds (hydrochlorofluorocarbons - HFC, perfluorocarbons - PFC, chlorofluorocarbons - CFC, and sulfur hexafluoride, SF_6).[1] However, various components of fine particulate matter ($PM_{2.5}$) in the atmosphere also have climate-forcing impacts, either contributing to or offsetting the effects of greenhouse gases.[2] In particular, black carbon particulate matter (BC) has recently been identified as an important contributor to radiative heating of the atmosphere.[3] Organic carbon particulate matter (OC), which is often emitted along with BC, may act to offset some of the global warming impact of BC emissions.[2]

Most of the important sources of greenhouse gases also are important sources of health-related pollutants. Likewise, BC and OC particulate matter are emitted primarily from combustion sources, which are also important sources of health-related pollutants. Because of these overlaps, measures to reduce climate-forcing emissions often would have collateral benefits by reducing emissions of health-related pollutants, and vice versa. Improved emissions inventory methodologies and tools developed for health-related pollutants can also provide opportunities for improving climate change emissions inventories (and vice versa).

A better characterization of worldwide emissions of climate forcing and health-related pollutants is needed to improve the understanding of overlapping benefits for emission reduction strategies both in the U.S. and abroad. The improved characterization of emissions will help in two ways: (1) by quantifying the most efficient strategies for improving both global warming and health-related problems, and (2) by identifying sources that are under-reported or missing from different emissions inventories. A full characterization of these under-reported or missing sources could alter the priorities of programs designed to mitigate both health-related and global climate impacts.

The purpose of the report is to twofold. First, a catalog is developed of country-specific and regional inventories for climate forcing pollutants and health related pollutants. The purpose of this catalog is to assist in the identification of opportunities for transfer of factors and methods among the different types of emissions inventories. Second, a review is made of tools and factors available to estimate particulate BC and OC emissions. The purpose of this review is to assist in identifying and prioritizing opportunities for improving U.S. and worldwide inventories of BC emissions.

BODY

Methods

We identified international inventories of climate change pollutants and health related pollutants by reviewing published literature, available government reports, and information posted on the Internet by government and international environmental agencies. To identify opportunities for improving BC emissions estimates, we compiled emission factors and particulate matter speciation factors used to develop BC inventories for climate change studies and compared these with other available data.

BC emissions for different emission source categories in the U.S. were estimated by applying speciation factors $PM_{2.5}$ emissions estimates from the EPA's National Emissions Inventory.[4] Global emissions for most source categories were estimated by applying BC emission factors to CO_2 emissions reported in the EDGAR climate change database.[5] Separate calculations were made for wildland fires, which are not included in most anthropogenic CO_2 emissions inventories. BC emissions from fires were estimated using average BC emission factors with fuel consumption estimates from Hao and Ward.[6]

Category-specific BC emissions estimates were used to identify areas where improved emission factors would have the greatest impact. The calculations focused both on the relative magnitude of estimated

BC emissions, and the relative uncertainty the estimates. Categories were also ranked based on the approximate magnitude of the uncertainty of BC emissions. The following equations were used in these evaluations:

Equation (1) $C(B)_i = (100 \times E(B)_i) / \Sigma_k E(B)_k$

Equation (2) $C(U)_i = (100 \times E(U)_i) / E(U)_i + \Sigma_{k \neq i} E(B)_k$

Equation (3) $Unc_i = E(U)_i - E(B)_i$

where

i and k = source categories contributing to BC emissions

C(B) = best estimate of the contribution of a particular source category to total emissions (%)

C(U) = upper end estimate of the contribution of the particular source category to total emissions (%)

Unc = uncertainty of emissions estimate for the particular source category

E(B) = best estimate of emissions from a given category

E(U) = upper end estimate of emissions from a given category

Σ_k = sum over all source categories

$\Sigma_{k \neq i}$ = sum over all categories except the particular source category i

Results and Discussion

<u>Available Emissions Inventories</u>

Country-specific inventories of climate change are compiled under the United Nations Framework Convention on Climate Change (UNFCCC).[7] Currently, over 180 countries subscribe to the agreement, although not all have produced climate change inventories. Climate change emissions inventories prepared under the UNFCCC generally conform with guidelines developed by the Intergovernmental Panel on Climate Change (IPCC).[8] These inventories typically focus on the greenhouse gases (CO_2, CH_4, N_2O, HFC, PFC, and SF_6); however, most also include volatile organic compounds (VOC), nitrogen oxides (NO_X), and carbon monoxide (CO) and many include other pollutants such as sulfur dioxide (SO_2). To date, the national climate change inventories do not include BC, OC, or particulate matter.

In addition to the country-specific climate change inventories, several organizations have produced regional or global inventories in varying degrees of resolution, ranging from a global 1^o latitude by 1^o longitude grid (about 100 kilometers x 100 kilometers near the equator) to country-wide inventories. For instance the European Core Inventory Air (CORINAIR)[9] compiles data developed in fulfillment of the UNFCCC as well as the the Convention on Long-Range Transboundary Air Pollution (LRTAP).[10] In addition to the pollutants listed above, the CORINAIR database includes selected persistent organic pollutants (POP) and trace metals.

We identified five global or regional emissions inventories that include BC. The Global Emission Inventory Activity (GEIA),[11] developed as part of the International Global Atmospheric Chemistry (IGAC) project, estimates global BC emissions in a $1^{o} \times 1^{o}$ grid, for an inventory base year of 1990. Global BC inventories have also been developed by Cooke et al, as part of ECHAM4;[12] by Cooke and Wilson,[13] and by Liousse et al.[14] Streets also developed a province-level BC emissions inventory for China as part of the CHINA-MAP project.[15] Two of these inventories, ECHAM4 and Liousse et al, include OC as well as BC.

Many countries produce separate inventories of health-related pollutants, including VOC, NO_X, SO_2, CO, PM, and toxic air pollutants. However these are considerably less widespread than climate change inventories. In addition, they are generally limited to industrial and combustion sources, neglecting sources such as consumer and commercial solvent usage. None of the health-related inventories provide BC or OC emissions.

Emission Factors and Other Tools for Estimating BC Emissions

Any analysis of BC emissions must recognize some unavoidable ambiguities in the definition of the pollutant. Carbon in particulate matter can take a variety of forms. Typically, these are divided into three main components: organic carbon (OC), a refractory component also known as elemental carbon (EC), and carbonate ion ($CO_3^{=}$). The split between EC and OC can be measured by different methods, but is typically obtained by measuring the amount that pyrolizes at different temperatures. Soot generally falls in the EC fraction.

For the purposes of climate change emissions inventories, BC is defined as the carbon component of particulate matter that absorbs light. However, this specific component of particulate matter is difficult, if not impossible, to measure. Methods that measure light absorption in particulate matter assume that BC is the only light absorbing component present, while methods that rely on the partitioning of EC and OC use a somewhat arbitrary division point. For the purposes of this analysis, we have treated BC as roughly equivalent to EC. However, some components of OC may also be light-absorbing; in this case, inventories of BC and OC may overlap.

Table 1 compares emission factors used in existing BC inventories, as well as other available information on BC emissions, for diesel vehicles and trucks. In many cases, BC emission factors were developed by combining BC speciation factors with appropriate particulate matter emission factors. Where possible, the table presents the BC speciation factors, the particulate matter emission factors, and the resultant BC emission factors. (In some cases, only an emission factor or a speciation factor is available.) Uncertainties are also given wherever possible. In addition to BC emission factors, Table 1 also includes OC emission factors, since the line between OC and BC is somewhat blurred. However, while some OC components may absorb light, most researchers presume that OC possesses optical properties that scatter solar radiation.[13, 14] Where possible, emission factors are given for BC and OC in particulate matter with an aerodynamic diameter of less than or equal to 2.5 microns ($PM_{2.5}$). In some cases, however, the literature used different measures, such as BC in $PM_{1.0}$ (submicron PM), or PM_{10} (less than or equal to 10 microns).

One important source of information on BC emissions is the body of particulate composition data developed over the last 20 years as part of "source apportionment" studies designed to identify the important emission sources contributing to elevated levels of respirable particulate matter. Many particulate matter fingerprints developed for these studies include EC which, as noted above, is roughly equal to BC.

EPA's SPECIATE database includes almost 200 measurements of the percentage of EC, OC, and other components of $PM_{2.5}$.[16] Other sources of particulate fingerprint data include: the California Air Resources Board (CARB) speciation manual,[17] measurements carried out under the Northern Front Range Air Quality Study,[18] and data compiled by Desert Research Institute.[19] BC emission factors can be estimated by applying EC speciation factors to $PM_{2.5}$ emission factors, from sources such as EPA's Compilation of Emission Factors (AP-42).[20] Alternatively, speciation factors can be applied directly to the $PM_{2.5}$ emissions inventories to estimate BC emissions. In addition, separate EC emissions estimates have been published for a number of emission source types as a result of fingerprint analyses.

Often, fingerprint data have already been incorporated in the emission factors used to produce BC emissions inventories. However, particulate source apportionment is an area of dynamic study, and as a result, the body of available particulate speciation data is continuously being expanded.

CONCLUSIONS

Opportunities for Improving Black Carbon Emissions Inventories

Table 1 illustrates the vast uncertainties in diesel vehicle emission factors. This statement also holds true even for stationary combustion sources. In many cases, these uncertainties could be reduced without additional measurements, by drawing on existing data to develop more detailed emission factors for specific subcategories of emission sources. In some cases, additional measurements may be needed.

In addition, BC emissions inventories developed to date have focused on industrial, utility, and residential combustion sources, as illustrated in Table 2. Less attention is devoted to industrial process emissions, nonroad mobile source emissions, and categories such as open burning.

Table 3 estimates BC emissions for the U.S. based on BC speciation factors and $PM_{2.5}$ emissions estimates from the EPA's 1999 NEI.[4] The table shows the NEI $PM_{2.5}$ emissions estimate for each category, a best estimate and upper end estimate for the BC speciation factor, and a best estimate and upper end estimate for BC emissions. Table 4 ranks different emission source categories according to their contribution to total U.S. emissions, based both on the best estimate and the upper end estimate of emissions. Categories are also ranked based on the approximate magnitude of the uncertainty of BC emissions.

Tables 5 and 6 show similar calculations for global BC emissions. We estimated global emissions in Table 5 by applying BC emission factors to fuel consumption figures, which for most categories were calculated from CO_2 emissions reported in the EDGAR climate change database.[5] In the case of wildland fires, fuel consumption was taken from an analysis by Hao and Ward.[6] It must be noted that the emissions in Table 5 are rough estimates developed without detailed activity data, for the purposes of ranking order of magnitude uncertainties. Table 6 ranks different emission source categories according to their estimated contribution to total global emissions, and to their uncertainties.

Based on the calculations in Tables 3 and 4, the largest BC emission source categories in the U.S. are nonroad and onroad diesel emissions. Nonroad diesel vehicle, residential incineration, and nonroad gasoline vehicles have caused the largest uncertainties in the overall inventory in terms of total emissions.

Disclaimer

This research was carried out for the U.S. EPA by EC/R Incorporated, Chapel Hill, North Carolina, in partial fulfillment of Contract No. 68-D6-046, Work 5-03. The opinions, findings, and conclusions expressed are those of the authors, and not necessarily those of the EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for their use.

Table 1. Comparison of Emission Factors and other Tools for Estimating BC and OC in Diesel Vehicles and Trucks

Category	PM-2.5 (g/kg)	Uncertainty	BC content (%)	Uncertainty	BC-2.5 (mg/kg)	Upper limit	OC content (%)	Uncertainty	OC-2.5 (mg/kg)	Upper limit	Reference
Previous inventories											
Underdeveloped countries			66	13	10,000				5000		Cooke et al[12]
Semideveloped countries			66	13	10,000				5000		Cooke et al[12]
Developed countries			66	13	2,000				1000		Cooke et al[12]
China	1.43	2.7	52	0	1,100	2,500					Streets et al[15]
Dynamoneter tests											
Diesel truck (1999 Ford F250)					850	884			408	442	Moosmuller et al[21]
Diesel truck (1996 Dodge Ram 2500)					329	340			397	431	Moosmuller et al[21]
1995 turbocharged intercooled engine			36.4				32				Shi et al[22]
Medium duty diesel trucks - 1999	1.6	0.2	30.8	2.6	480	580	19.7	1.6	310	370	Shauer[23]
Light duty diesel 1996 - Denver	6.0		27		1,600		18		1,100		Cadle et al[24]
MOBILE model average	0.53										EPA NEI[4]
Field tests											
Tunnel test 1997 - heavy duty diesels (CA)	2.5	0.2	52	16	1,300	1,600	20	3	500	540	Kirchstetter et al[25]
Tunnel test 1993 - heavy duty vehicles (CA)	2.68	0.19	56	6.3	1,518	1,582	32	2.6	848	857	Allen et al[26]
Tunnel test 1993 - heavy duty vehicles (CA)	1.53	0.28	61	38	936	1,330	39	16	588	713	Allen et al[26]
Tunnel, Switzerland, 1993 - diesel	2.6	0.1	31	3.4	823	880					Weingartner et al[27]
Tunnel, Switzerland, 1993 - heavy duty	2.1	0.1	32	2.4	687	719					Weingartner et al[27]
Fingerprint - Arizona			33	8.0	174		40	6.6	213		Watson et al[28]
SPECIATE - heavy duty diesel			50	7.2			31	7.1			SPECIATE[16]
SPECIATE - light duty diesel			60	12			30	10			SPECIATE[16]
Best estimates											
Diesel vehicles,			43	15	1,100	1,600	29	8	645	900	

developed countries

Table 2. Source Categories Covered by Black Carbon Emissions Inventories

Source Category		Inventory				
		Cooke and Wilson	ECHAM4 (Cooke)	GEIA (Penner)	Louisse et al.	Streets et al.
Residential fuel	Coal	T	T[a]	T	T	T
	Oil/diesel	T	T		T	T
	Biofuel	T	T	T	T	T
	Natural Gas	T	T			
Industrial and utility fuel	Coal	T	T	T		T
	Oil	T	T			T
	Biofuel	T	T	T		T
	Gas	T[b]	T			
	Petroleum	T	T			
	Kerosene	T	T			
On-road mobile	Diesel			T		T
	Gasoline	T	T			T
Non-road mobile	Marine vessels					T
	Aircraft	T	T			
	Other					T
Fire	Wildland fire	T			T	
	Agricultural burning				T	T

[a] also includes briquettes, coke oven coke, gas coke, brown coal coke, lignite brown coal

[b] includes natural, blast furnace, coke-oven, gasworks, and refinery gases

Table 3. Estimated Breakdown of BC Emissions in the U.S.

Category	Reported US $PM_{2.5}$ emissions (1000 Mg/yr)	BC to $PM_{2.5}$ ratio (%)		Estimated BC emissions [c] (1000 Mg/yr)	
		Best estimate	High estimate	Best estimate	High estimate
Electric utilities - coal	92	3.7	7.1	3.0	7.0
Electric utilities - petroleum	4.0	7.4	13	<0.1	<0.1
Electric utilities - natural gas	17	6.7	15	1.0	3.0
Electric utilities - wood/other	3.0	9.3	31	<0.0	1.0
Industrial combustion - coal	21	3.7	7.1	1.0	2.0
Industrial combustion - petroleum	22	7.4	13	2.0	3.0
Industrial combustion - natural gas	49	6.7	15	3.0	7.0
Industrial combustion - wood	44	9.3	31	4.0	14
Commercial combustion - coal	7.0	3.7	7.1	<0.1	<0.1
Commercial combustion - petroleum	4.0	7.4	13	<0.1	<0.1
Commercial combustion - natural gas	7.0	6.7	15	<0.1	1.0
Residential combustion - natural gas	13	6.7	15	1.0	2.0
Residential combustion - wood	340	6.1	9.0	21	31
Onroad diesel vehicles	151	43	59	65	89
Onroad gasoline vehicles	58	27	60	16	35
Marine transportation	36	43	59 [a]	16	21
Locomotives - diesel	25	43	59 [a]	11	15
Aircraft	25	70		17	25
Nonroad - gasoline	75	27	60 [a]	20	45
Nonroad - diesel	211	43	59 [a]	91	125
Miscellaneous fuel combustion	73	14	24	10	18
Wildfires	212	7.2	12	15	25
Prescribed forest burning	478	7.2	12	34	56
Agricultural burning	85	12	13	10	11
Open burning - residential	157	12	13 [b]	19	21
Open burning - other	275	12	13 [b]	34	36
Incineration - residential	28				28
Incineration - other	15				15
Industrial - metals processing	94	10	30	9.0	28
Industrial - asphalt manufacture	4.0				4.0
Industrial - peteoleum refining	12	0.3	0.4	<0.1	<0.1
Oil and gas production	1.0				1.0
Rubber and plastics products	2.0				2.0
Fugitive dust - unpaved roads	1,283	1.0	1.9	12	24
Fugitive dust - paved roads	620	1.7	2.8	11	17
Fugitive dust - construction	355		0.5		2.0
Fugitive dust - other	133	0.6	1.3	1.0	2.0
Agriculture - tilling	782		0.6		5.0
Agriculture - livestock	81	6.0	8.0	5.0	6.0
Total	5,894			433	727

a - Estimated based on information for onroad vehicles.

b - Estimated based on information for agricultural burning.

c - The BC emissions estimates in this table were developed as part of this current study. Although they are based in part on the $PM_{2.5}$ component of the EPA NEI, they should not be construed as a part of the NEI.

Table 4. Ranking of U.S. Source Categories by BC Emissions and Uncertainty

Category	Contribution to total U.S. BC emissions (%): Based on best estimate	Contribution to total U.S. BC emissions (%): Based on upper end estimate	Uncertainty of BC estimate (1000 Mg/yr)	Rankings of importance: Based on share of BC: Best estimate	Rankings of importance: Based on share of BC: Upper	Rankings of importance: Based on uncer-tainty
Electric utilities - coal	0.8	1.5	3.1			
Electric utilities - petroleum	0.1	0.1	0.2			
Electric utilities - natural gas	0.3	0.6	1.4			
Electric utilities - wood/other	0.1	0.2	0.6			
Industrial combustion - coal	0.2	0.3	0.7			
Industrial combustion - oil	0.4	0.6	1.2			
Industrial combustion - gas	0.8	1.7	4.1			
Industrial combustion - wood	1.0	3.1	9.8			
Commercial combustion - coal	0.1	0.1	0.2			
Commercial combustion - oil	0.1	0.1	0.2			
Commercial combustion - gas	0.1	0.2	0.5			
Residential combustion - gas	0.2	0.4	1.1			
Residential combustion - wood	4.8	6.9	9.8	5	7	10
Onroad diesel vehicles	15	19	24	2	2	4
Onroad gasoline vehicles	3.6	7.7	19	10	6	6
Marine transportation	3.6	4.9	5.8	9		
Locomotives - diesel	2.5	3.3	4.0			
Aircraft	4.0	5.6	7.4	8		
Nonroad - gasoline	4.7	9.8	25	6	4	3
Nonroad - diesel	21	27	34	1	1	1
Miscellaneous fuel combustion	2.4	4.0	7.3			
Wildfires	3.5	5.6	9.5		10	
Prescribed forest burning	7.9	12	22	3	3	5
Agricultural burning	2.4	2.6	0.8			
Open burning - residential	4.4	4.7	1.4	7		
Open burning - other	7.7	8.3	2.5	4	5	
Incineration - residential		6.1	28		9	2
Incineration - other		3.2	15			8
Industrial - metals processing	2.2	6.2	19		8	7
Industrial - asphalt manufacture		0.9	3.8			
Industrial - peteoleum refining	<0.1	<0.1	<0.1			
Oil and gas production		0.1	0.6			
Rubber and plastics products		0.5	2.0			
Fugitive dust - unpaved roads	2.9	5.4	12			9
Fugitive dust - paved roads	2.4	3.9	6.8			
Fugitive dust - construction		0.4	1.8			
Fugitive dust - other	0.2	0.4	1.0			
Agriculture - tilling		1.1	4.7			
Agriculture - livestock	1.1	1.5	1.6			

Table 5. Estimated Breakdown of Global BC Emissions

Source category	Reported global CO_2 emissions	BC emission factors (mg/kg) Best estimate	BC emission factors (mg/kg) Upper end	Estimated BC emissions (10^6 Mg) Best estimate	Estimated BC emissions (10^6 Mg) Upper end	Notes on emission factors
Fossil fuel combustion						
Industrial boilers	4,590	130	770	0.60	3.5	a
Power generation	6,638	130	770	0.86	5.1	b
Industrial process fuel	1,624	130	770	0.21	1.3	a
Residential, etc.	3,343	1,350	7,000	4.5	23	c
Road transport	3,261	570	1,360	1.9	4.4	d
Non-road land transport	343	500	1,600	0.17	0.55	e
Air (domestic and int'l.)	545	110	150	0.06	0.08	f
International shipping	350	200	1,150	0.07	0.40	g
Fossil fuel: non-combustion						
Gas flaring	260	0.01	0.03	<0.01	<0.01	h
Biofuel						
Industrial boilers	118	1,000	10,000	0.12	1.18	i
Other industry fuel use	1	1,000	10,000	0.00	0.01	i
Residentials etc.	427	675	1,880	0.29	0.80	
Other						
Deforestation	1,837	730	1,430	1.3	2.6	
Savannah fires (j)	5,200	130	500	0.68	2.6	
Forest fires (j)	620	730	1,430	0.45	0.89	
Total				21	90	

a Average of coal stoker, residual oil, and natural gas from Streets et al[15]
b Average of coal stoker, pulverized coal, and residual oil from Streets et al[15]
c Average of coal, oil, and natural gas from Streets et al[15]
d Upper end estimate is average of diesel from Streets et al[15]
e Average of coal stoker, residual oil, and diesel from Streets et al[15]
f Based on jet fuel factors from Petzold et al[29]
g Average of coal stoker and residual oil from Streets et al[15]
h Based on Cooke et al[12] for natural gas combustion
i Based on Streets et al[15]
j Biomass burned in wildland fire from Hao and Ward[30]

Table 6. Ranking of Source Categories by Global BC Emissions and Uncertainty

Category	Based on best estimate	Based on upper end estimate	Uncertainty of BC estimate (10^6 Mg/yr)	Based on share of BC: Best estimate	Based on share of BC: Upper	Based on uncer-tainty
Fossil fuel: combustion						
Industrial boilers	5.3	25	2.9	6	4	3
Power generation	7.7	33	4.2	4	2	2
Industrial process fuel	1.9	10	1.0	8	7	8
Residentials etc.	40	78	19	1	1	1
Road transport	17	32.1	2.6	2	3	4
Non-road land transport	1.5	4.7	0.4	9	10	10
Air (domestic + intern.)	0.5	0.7	<0.1			
International shipping	0.6	3.5	0.3			
Fossil fuel: non-combustion						
Gas flaring	<0.1	<0.1	<0.1			
Biofuel						
Industrial boilers	1.0	9.6	1.1	10	8	7
Other industry fuel use	<0.1	0.1	<0.1			
Residentials etc.	2.6	6.8	0.5	7	9	9
Other						
Deforestation	12	21	1.3	3	5	6
Savannah fires	6.0	20	1.9	5	6	5
Forest fires	4.0	7.6	0.4			

REFERENCES

1. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, 2000; p 1.3.
2. Hansen, James E. and Makiko Sato. "Trends of measured climate forcing agents." *Proceedings of the National Academy of Sciences of the United States of America* 2001, 98, 26, 14778-14783.
3. Jacobson, Mark Z. "Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols." *Nature* 2001, 409, 6821, 695-697.
4. *National Emissions Inventory*. U.S. Environmental Protection Agency, Emission Factors and Inventory Group, Research Triangle Park, NC. Data available: http://www.epa.gov/ttn/chief/net /index.html
5. Olivier et al. "Description of EDGAR Version 2.0: A set of global emission inventories of greenhous gases and ozone-depleting substances for all anthropogenic and most natural sources on a per country basis and on $1^o x 1^o$ grid." *National Institute of Public Health and the Environment (RIVM)* report no. 771060 002 / TNO-MEP report no. R96/119, 1996. 1999 data available: http://www.rivm.nl/env/int/coredata/edgar/index.html
6. Hao, Wei Min, and Darrold Ward. "Methane production from global biomass burning." *Journal of Geophysical Research* 1995, 98, 20,657-20,661.
7. *Guide to the Climate Change Negotiation Process*, United Nations Framework Convention on Climate Change (UNFCCC), June 21, 2001. Available: http://www.unfccc.int/resource/process.
8. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3: Reference Manual*, IPCC; 1996.
9. *European Air Emissions for 1994*; CORINAIR94 database, September 16, 1997. Available: http://www.aeat.co.uk/netcen/corinair/94.
10. *1979 Convention on Long Range Transport of Air Pollutants (LRTAP)*; United Nations Economic Commission for Europe (UNECE). Treaty text available: http://www.unece.org/env/lrtap/conv/lrtap_c.htm.
11. Penner et al. "Towards the development of a Global Inventory for Black Carbon Emissions." *Atmospheric Environment* 1993, 27A, 1277-1295. Data Available: http://weather.engin.umich.edu/geia/emits/data.html
12. Cooke, W.F. et al. "Construction of a 1^o x 1^o fossil fuel emission data set for carbonaceous aerosol and implementation and radiative impact in the ECHAM4 model." *Journal of Geophysical Research* 1999, 104, D18, 22,137-22,162.
13. Cooke, W.F. and Julian J.N. Wilson. "A global black carbon aerosol model." *Journal of Geophysical Research* 1996, 101, D14, 19,395-19,409.
14. Liousse, C. et al. "A global three-dimensional model study of carbonaceous aerosols." *Journal of Geophysical Research* 1996, 101, D14, 19,411-19,432.
15. Streets, David G. et al. "Black Carbon emissions in China." *Atmospheric Environment* 2001, 35, 4281-4296.

16. *SPECIATE version 3.1 model*, U.S. Environmental Protection Agency, Research Triangle Park, NC. October 1999. Data available: http://www.epa.gov/ttn/chief/software/speciate/index.html

17. "Identification of Particulate Matter Species Profiles," *ARB Speciation Manual, Second Edition, Volume 2*; California Air Resources Board, Sacramento, CA, 1999.

18. Zielinska, Barbara, et al. "Northern Front Range Air Quality Study Final Report–Volume B: Source Measurements." Prepared for Colorado State University by Desert Research Institute, Reno, NV. 1998.

19. Chow, Judith C. and John G. Watson. *Imperial Valley/Mexicali Cross Border PM10 Transport Study*, Desert Research Institute, Reno, NV, 1995; DRI Document No. 8623.2D1.

20. *Compilation of Air Pollutant Emission Factors, Volume I, AP-42*. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1991, Section 13.

21. Moosmuller, H. et al. "Time-Resolved characterization of Diesel Particulate Emissions. 2. Instruments for Elemental and Organic Carbon Measurements." *Environmental Science and Technology* 2001, 35, 1935-1942.

22. Shi, J Ping, David Mark, and Roy M. Harrison. "Characterization of Particles from a Current Technology Heavy-Duty Diesel Engine." *Environmental Science and Technology* 2000, 34, 748-755.

23. Shauer, J.J. "Measurement of Emissions from Air Pollution Sources. 1. C1 through C30 Organic Compounds from Medium Duty Diesel Trucks." *Environmental Science and Technology* 1999, 33, 1578-1587.

24. Cadle, Steven H. et al. "Particulate Emission Rates from In-Use High-Emitting Vehicles Recruited in Orange County, California." *Environmental Science and Technology* 1997, 31, 3405-3412.

25. Kirchstetter, Thomas W. et al. "On-road measurement of fine particle and nitrogen oxide emissions from light- and heavy-duty motor vehicles." *Atmospheric Environment* 1999, 33, 2955-2968.

26. Allen, Jonathan et al. "Emissions of Size-Segregated Aerosols from on-road Vehicles in the Caldecott Tunnel." *Environmental Science and Technology*, 2001, 35 (21), 4189-4197.

27. Weingartner, E. et al. "Aerosol Emission in a Road Tunnel." *Atmospheric Environment* 1997, 31 (3), 451-462.

28. Watson, John G., Judith C. Chow, Zhiquiang Lu, Eric Fujita, Douglas Lowenthal, Douglas Lawson, and Lowell Ashbaugh. "Chemical Mass Balance Source Apportionment of PM-10 during the Southern California Air Quality Study." *Aerosol Science and Technology* 1994, 21, 1-36.

29. Petzold, A. et al. "Carbonaceous aerosol in jet engine exhaust: emission characteristics and implications for heterogeneous chemical reactions." *Atmospheric Environment* 1999, 33, 2689-2698.

30. Hao, Wei Min, and Darrold Ward. "Methane production from global biomass burning." *Journal of Geophysical Research* 1993, 98, 20,657-20,661.

KEYWORD

Black Carbon
Organic Carbon
Emission Inventory
Particulate Matter