Black Smoke in China and Its Climate Effects*

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Abstract
The emission of fine carbonaceous particles in China is a serious threat to human health, ecological systems, and regional and global climate regimes. China is thought to release about 20 percent of the global black carbon through the combustion of coal and biofuels without adequate particle controls. The household and industrial sectors are mainly responsible, but the country's growing transportation sector is a concern for the future. The economic cost of damage from black carbon likely exceeds the cost of controlling emissions by several fold, but as yet such costs have not been quantified.

1. Introduction

Black smoke is apparent to any visitor to China. Small industrial chimneys dot the landscape, many of them emitting dark-colored plumes of smoke. The sources of this smoke are usually coal-fired ovens, kilns, or small boilers that fuel what are often little more than family enterprises. Rural villages are bathed in a silvery mist caused by smoke from cooking and heating over coal, wood, or crop-waste fires in homes. Vehicles often release visible tailpipe emissions. Farmers burn the crop residues in the fields after harvest or in preparation for new planting. These individual sources combine to produce a regional haze that lingers over the countryside and cities. This pollution causes economic, ecological, and human health damage,

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all largely unquantified, and poses several questions: What is this material? What kinds of hazards does it cause? What can be done about it? This paper examines the important but little-appreciated problem of black smoke in China; in particular, the sources and measurement of such emissions, the likely effects on global and regional climate, and implications for air pollution and global warming policy. Study of these issues reveals surprising opportunities for making large improvements in several important areas.

The active ingredient in this black smoke and grayish-brown haze is the aerosol known as black carbon (BC). It is similar to elemental carbon but may have other chemicals combined with it. Most BC particles are less than 1 μm (10^{-6} meter) in diameter. Because the particles are small, they have a long atmospheric residence time, ranging from a few days to several weeks (Cooke and Wilson 1996; Liousse et al. 1996), and may therefore spread hundreds to thousands of kilometers before they fall back to earth. BC is thought to be the anthropogenic aerosol component that contributes the most to the absorption of solar radiation (Penner, Eddleman, and Novakov 1993; Cooke and Wilson 1996; Liousse et al. 1996). In this respect, it is no different from greenhouse gases such as carbon dioxide.

BC also causes other, more immediately evident, problems. Qiu and Yang (2000) have shown that BC contributes to the marked degradation of visibility in northern China. Chameides et al. (1999) demonstrated that crop yields in China are lowered by 30 percent because of reduced solar radiation reaching the earth. Fine particles may coat building materials, damaging the appearance of homes, public buildings, and historic landmarks (Hamilton and Mansfield 1991). These very small particles can penetrate deeply into the lungs, where they may slow clearance mechanisms and provide absorption sites for toxic pollutants (Hamilton and Mansfield 1991). Because the majority of BC emissions originate in the residential sector, where exposure levels are high as a result of the poor ventilation in most homes and kitchens in China, the negative effects of inhalation of BC on public health are important. In summary, emissions of black smoke are of concern at the household, regional, and global level.

Until a few years ago, aerosols such as BC languished in the shadows of atmospheric research. We did not fully understand their roles in atmospheric chemistry or in the scattering and absorption of radiation. Aerosols were difficult to measure in the field and in the laboratory, difficult to model, and had complex chemical and physical characteristics. BC emissions were relevant to pollution policy only insofar as they contributed to the amount of fine particles in general. The regulation of inhalable particulate matter (PM) in the developed world signaled that high local concentrations in cities were a public health concern. As research on the impacts of airborne PM on public health progressed, the effects of submicron particles such as BC were increasingly understood to be important.

The importance of aerosols on a regional scale gradually became understood. We learned that aerosols play important roles in regional air quality because they contribute to haze, impaired visibility, and reduced insolation. The importance of aerosols on a global scale was soon recognized, when further research showed that they play a significant role in climate modification (Penner, Hegg, and Leaitch 2001). Within the past several years, the importance of BC as a factor in global climate change has come to the forefront. Work by Hansen, Jacobson, and others shows that BC is perhaps the second-most-important contributor to global warming, after CO_2. This understanding is beginning to have profound reverberations in both the policy arena and the world of research planning. BC poses an array of problems not previously faced in air pollution control regimes; however, it is difficult to measure accurately, a large proportion of global BC emissions arises from unmonitored biomass burning, and the fuel-derived sources are unconventional, in the sense that they are largely domestic stoves and small industrial plants. Finally, the largest BC-emitting country in the world is China.

Acknowledging the major role of China in BC production is the first step, but balancing the economic, health, and other issues involved in tackling the problem is far from easy. Nevertheless, the control of BC offers major opportunities to attack simultaneously (1) health effects at the local level, (2) ecosystem damage at the regional level, and (3) climate change at a regional and global level. In addition, the costs of reducing BC emissions are considerably less than those related to controlling greenhouse gases such as CO_2. This multipronged weapon is therefore intriguing for policymakers.

2. Sources of black smoke

BC is released during the incomplete combustion of carbonaceous fuels. It is important to note that the terms used to classify carbonaceous aerosols can vary with the measurement method (see “Measurement uncertainties,” below). Because the primary interest in BC at present centers on its ability to absorb solar radiation, it is usual to define BC as the mass of elemental carbon (EC) that absorbs the same amount of light as the emitted particles, though carbon that absorbs light may not be black and its molecular form may differ from that of EC (Bond 2001). A related aerosol is organic carbon (OC), in which the carbon is in more complex molecular forms. This paper does not address OC.

Emissions of BC are difficult to determine under the best of circumstances because of difficulties in estimating the fraction of total PM that is EC of less than 1 μm in diameter. This fraction is very sensitive to fuel type and combustion conditions, necessitating a detailed treatment of emission factors by fuel, sector, and degree of emission control. Uncertainty about BC emission levels is particularly high for coal combustion because larger particles, organic compounds, and mineral ash can confound measurements of very small particulates. Such problems are compounded when dealing with developing countries, where no statistics are available on the types and prevalence of combustors and the kinds and performance of devices that control particulates.

Early research suggested that China generates a sizeable proportion of global BC emissions as a result of the widespread and uncontrolled burning of coal. To get a better perspective on BC emissions in China, Streets et al. (2001a) conducted a detailed investigation of BC sources, part of which consisted of a thorough review and assessment of studies by combustion experts on fine particle emissions. In this way, a robust set of emission factors was developed for different source types, integrated with measurements of particle emission factors and appropriate submicron and carbonaceous fractions. Streets et al. (2001a) found that the residential burning of coal yielded a midrange estimate for the BC emission factor of 3.7 g/kg of coal, with a high estimate of 20 g/kg. Residential biofuel burning was estimated to be 1.0 g/kg. Field combustion of agricultural residues is in the range of 0.5–0.9 g/kg. In contrast, the emission factor for a conventional coal-fired power plant using an electrostatic precipitator (ESP) is only 0.0001 g/kg. This is because the very high temperatures and efficient air circulation in large boilers readily oxidize any fine carbon particles leaving the combustion zone; thus, it is primarily mineral matter that escapes, and it is either captured in the particulate control device or passes through into the atmosphere. The estimated emission factor for heavy fuel oil in China is 0.36 g/kg and that for diesel vehicles is 1.1 g/kg. These new values suggested a significantly different pattern of source contributions than that of previous work.

The China inventory was extended to a global inventory for 1996 (Bond et al. 2004), which revealed the contribution of China to global emissions (table 1). The total amount of global BC emissions according to this new inventory is 7.95 Tg (1 teragram [Tg] = 1 million metric tons). China contributes about 18.7 percent of the total BC emissions. The developing regions of Africa and South America are also important contributors. The developed regions of the world (e.g., North America, Europe, and Japan), however, are less significant contributors to BC emissions than they are to CO_2 emissions. Thus, China dominates BC emissions, whereas the United States

Table 1. Contributions from various countries to global CO_2 and BC emissions

	United States	Mexico	Germany	United Kingdom	Japan	China	India	Global
CO_2 (Tg)	5,576	397	983	596	1,285	3,749	991	26,939
CO_2 (%)	20.7	1.5	3.6	2.2	4.8	13.9	3.7	100.0
BC (Tg)	0.41	0.08	0.05	0.04	0.15	1.49	0.58	7.95
BC (%)	5.2	1.0	0.6	0.5	1.9	18.7	7.3	100.0

Sources: *Chameides and Bergin (2002); BC emissions from Bond et al. (2004).*

Note: *Tg = 1 teragram = 1 million metric tons.*

dominates CO_2 emissions, which begins to point toward an opportunity for joint action. (I expand upon this issue at the end of the paper.)

Estimates of BC emissions in China by source type are summarized in table 2. Estimates have been made for 1995, and emission levels have been projected for 2020. The emission estimates reveal significant sectoral differences (e.g., residential and agricultural contributions) that set BC apart from sulfur dioxide (SO_2) and nitrogen oxides (NO_x), the traditional anthropogenic pollutants that mainly originate from the industrial and power generation sectors. And, although vehicle pollution is an important source of NO_x and hydrocarbon pollution in other parts of the world, the role of vehicles in the deterioration of air quality in China is still relatively small. If the number of diesel trucks were to grow rapidly in China in the future, this would likely cause serious increases in fine particles and BC. Efficient tailpipe controls will be required to prevent a large increase in emissions.

2.1 Power generation

Particulate emission levels from power generation are low because combustion conditions in power plants (predominantly pulverized-coal burners) tend to burn out any BC that is formed. Furthermore, all new power plants and many large, old power plants in China use ESPs to collect PM. In 1983, only 25 generating units were equipped with ESPs, but by 1991 this had increased to 236 units, and by 1993 the number had grown to 316 units (Zhai 1992; SSTC 1995). By 1995, there were 364 ESP units, fitted to approximately 50 percent of China's total boiler capacity (Bo et al. 1999). On older, midsized, and small power generation units, wet particle scrubbers are employed, together with some multicyclones and cyclones (inefficient mechanical devices that rely on a spinning motion to remove particles), which are gradually being eliminated.

Energy consumption for power generation in China in 1995 from coal, oil, and biofuels was 10.9 EJ (EJ = exajoule = 10^{18} joules), of which 10.1 EJ (92 percent) was

Table 2. Summary of estimated energy use and BC emissions in China, by sector and fuel type

		Energy use (PJ)		BC emissions (Gg)	
Sector	**Fuel**	**1995**	**2020**	**1995**	**2020**
Residential	Coal	3,872	4,848	605.4	534.8
	Oil	432	2,088	1.0	5.5
	Biofuel	7,939	6,016	512.0	386.8
	Subtotal	12,243	12,952	1,118.4	927.1
Industry	Coal	13,171	18,257	82.5	80.6
	Oil	2,040	2,513	11.1	14.5
	Biofuel	600	482	3.6	1.4
	Subtotal	15,811	21,252	97.2	96.5
Power generation	Coal	10,080	18,054	1.5	0.1
	Oil	731	607	6.1	4.8
	Biofuel	89	226	0.7	0.5
	Subtotal	10,900	18,887	8.3	5.4
Transportation: road	Gasoline	1,208	4,047	2.3	7.6
	Diesel	508	2,798	13.3	73.3
Transportation: other	Gasoline	100	139	0.2	0.3
	Diesel	764	1,644	20.0	43.1
	Coal	234	277	3.2	3.7
Transportation: ships	Diesel	138	328	3.6	8.6
	Heavy fuel oil	87	308	0.8	2.7
	Subtotal	3,039	9,541	43.4	139.3
Field combustion	Crop residue	n.a.	n.a.	74.7	56.1
All sources	Total	41,993	62,632	1,342.0	1,224.4

Source: *Streets et al. (2001a).*

Note: *n.a. = data are not available.*

derived from coal (see table 2). The 731 PJ (PJ = petajoule = 10^{15} joules) of oil combustion are also important, however, because this source has significantly higher BC emission factors. An energy projection for 2020 by Li (1999) shows coal combustion rising to 18.1 EJ and oil combustion declining to 607 PJ. About 226 PJ of advanced renewable energy (e.g., biogas and waste combustion) are expected to be consumed in China by 2020. After a detailed categorization of the different types of boilers and emission-control devices (table 2), we estimate that BC emissions from power generation were 8.3 Gg in 1995. Most of these emissions (73 percent) resulted from oil combustion. Emissions from coal combustion are estimated to be only 1.5 Gg because of the effective use of particulate controls. We estimate that BC emissions from power generation will decline to 5.4 Gg in 2020 as the power sector eliminates cyclone controls, reduces oil use, and transforms to a coal-based system that employs high-efficiency ESP and fabric-filter controls.

2.2 Industrial fuel combustion

The complexity of the industrial sector in China, with respect to the variety of fuels, combustors, and control devices in use, makes accurate estimation of BC emissions very difficult. Because of the greater attention paid to industrial combustion processes and emission controls, however, these facilities tend to have lower emissions than do domestic devices. Total industrial energy use in 1995 from liquid and solid fuels was 15.8 EJ, of which 13.2 EJ (83 percent) were provided by coal. This is expected to rise to 21.3 EJ by 2020, with coal's share rising to 18.3 EJ (86 percent). Streets et al. (2001a) suggests that, by 2020, use of stoker-fired industrial combustors with no control devices or cyclones will decline and use of stokers with wet particle scrubbers and pulverized-coal systems with advanced pollution controls such as ESP will increase. At present, industrial BC emissions are primarily attributable to uncontrolled coal-fired kilns, ovens, and stoker-fired boilers and from the production and use of coke in the iron and steel industry. As shown in table 2, the total coal-derived emissions in 1995 are estimated at 82.5 Gg (85 percent of the industrial sector total of 97.2 Gg). Industrial BC emissions are projected to remain approximately unchanged from 1995 to 2020. A decline in the use of raw coal in uncontrolled or poorly controlled industrial boilers, kilns, and furnaces is expected to be offset by an increase in oil use.

2.3 Residential sector

By far the largest contribution to BC emissions in China comes from the burning of raw coal, coal briquettes, and biofuels in the residential sector. These fuels are burned in small domestic stoves, cookers, and heaters without any emission controls. Emission of fine particles is greatly enhanced under these conditions. We estimate that, in 1995, Chinese households consumed 241 PJ of coal briquettes and 3,630 PJ of raw coal (briquettes accounting for 6 percent of total domestic coal use). The use of briquettes was highest in Anhui, Hebei, Jiangsu, Shaanxi, and Sichuan provinces and in the municipalities of Beijing and Shanghai. Briquettes are increasingly being burned in the largest cities of China, and raw coal is being phased out or banned. We have projected briquette use for 2020, assuming that 100 percent of coal use in the largest cities is in the form of briquettes, 50 percent in towns, and 20 percent in the countryside. This yields 2020 estimates of 1,996 PJ for briquettes and 2,851 PJ for raw coal, briquettes accounting for 41 percent of domestic coal use (Streets et al. 2001a).

In 1995, biofuels dominated China's rural energy supply, whereas coal use was widespread in urban residential areas. Overall, 7.9 EJ of biofuels and 3.9 EJ of coal were used. By 2020, biofuel use is expected to decline to 6 EJ and coal use is projected to increase to 4.8 EJ. Even though coal is being replaced by natural gas in the cities, coal is expected to supplant biofuels in many of the smaller towns in coal-producing regions. Domestic coal combustion is the dominant source of BC in both 1995 and 2020, with emissions of 605 Gg and 535 Gg, respectively. The increased use of coal briquettes in urban areas is expected to reduce BC emissions by 2020. Although the use of biofuels is declining in China, the high emission rates from this source have resulted in BC emissions of 512 Gg in 1995, and emissions are estimated to be approximately 387 Gg in 2020. Overall, the residential sector generated 1,118 Gg of BC in 1995 and is projected to generate 927 Gg in 2020. This represents 83 percent and 76 percent, respectively, of total emissions. The key to the reduction of BC emissions in China is the transformation of the domestic sector from one based on the combustion of raw coal and biofuels in small cookers and heaters to one that increasingly uses coal briquettes, liquefied petroleum gas, natural gas, electricity, or renewable energy sources.

2.4 Transportation sector

Emissions originating from the transportation sector were relatively low in 1995 (43 Gg), but they are expected to more than triple by 2020, to 139 Gg, as a result of a large increase in motor vehicle ownership. By 2020, the transportation sector will account for 11 percent of total BC emissions. Vehicles fueled with gasoline have very low PM emissions. No PM emission controls are employed on these vehicles, nor is it expected that PM emission controls will be employed in future gasoline-powered vehicles. Vehicles fueled with diesel fuels usually have high PM emissions. In the United States, new emission standards will probably require application of PM emission controls to diesel vehicles. PM emissions from diesel vehicles, however, are still low relative to PM emissions from some stationary sources. It is not likely that Chinese diesel vehicles will employ PM emission controls during the next 20 years, in light of the lag of emission controls for Chinese motor vehicles relative to U.S. motor vehicles. As existing units are replaced, however, the number of vehicles with high emissions due to engine failure or other reasons will gradually decrease. China is clearly interested in increasing its use of diesel vehicles for reasons of energy efficiency: the projections show an increase in energy for diesel vehicles from 1.3 EJ in 1995 to 4.4 EJ in 2020. Tailpipe emissions of PM from diesel vehicles will be an important problem for human health in Chinese cities in the future.

2.5 Field combustion of crop residues

The burning of crop residues in the field, as a means of disposal after harvesting or before planting, is a common practice in China despite being officially banned. The BC emissions from this source are significant. Several assumptions have to be made to estimate how much BC this type of combustion produces. Crop production statistics, available by province and crop (FAO 1995), are combined with crop-to-residue ratios (Lu 1993) to calculate available regional crop residues. Although other crop residues may be burned in the fields, our emissions are calculated on the basis of data for the three largest crops: rice, wheat, and corn. In Asia, approximately 80 percent of crop residue is burned, including that used for domestic fuel (Crutzen and

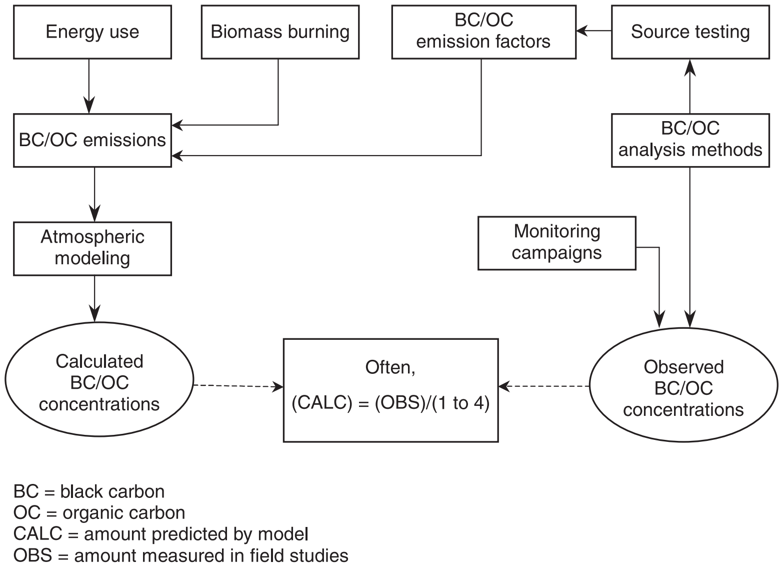
Andreae 1990). The residue burned in fields makes up approximately 23 percent of the total residue produced. Although rice husks constitute the bulk of the residue burned in fields, no data were found on precise quantities, so a flat rate of 23 percent of available residue is applied to rice, wheat, and corn residues. On the assumption that farmers will reduce their burning rate in the future under local environmental pressures, our calculations yield estimates for BC emissions from field combustion of 75 Gg in 1995, falling to 56 Gg in 2020.

3. Measurement uncertainties

A clear understanding of the role of BC in climate change requires an ability to measure BC concentrations in the ambient atmosphere and predict BC concentrations using emissions and simulation models. This ability is hindered by inherent uncertainties in BC measurements. There are two fundamentally different ways to measure BC in the atmosphere: thermal and optical. The thermal method analyzes aerosol samples collected on quartz filters. The samples are heated, and the volatilized carbon is collected and measured as a function of temperature. Residues remaining above a certain temperature are presumed to be elemental carbon, though they may be contaminated with organic compounds with low volatilities and high molecular weights. Different thermal analysis equipment and operating techniques have yielded results that differ by a factor of two or more. The optical method measures the aerosol absorption coefficient and relates it to BC mass concentration. Optical techniques are also subject to considerable uncertainty. This uncertainty associated with thermal and optical measurements has obscured the job of using models to simulate BC concentrations. The need for a standardized BC measurement method is clear.

Experience with global modeling of BC seems to support this conclusion. A number of research groups have simulated global BC concentrations with atmospheric models and compared them with observations at ground stations (Tegen et al. 2000; Koch 2001; Chin et al. 2002; Jacobson 2002; Cooke, Ramaswamy, and Kasibhatla 2002). The AERONET database provides a network of 20 global sites with field measurements, against which one can compare emission concentrations calculated from models. BC emissions are typically underpredicted, sometimes by a factor of two to four, which suggests that emissions are actually higher than estimated by inventory methods. This is surprising, because global BC emissions used in the models (Cooke and Wilson 1996) are already high (17–18 Tg/year, according to Chin et al. 2002). Recent field measurements of BC by use of aircraft-borne sampling equipment (Dickerson et al. 2002; Clarke et al. 2004) have occasionally observed very high concentrations of BC, as much as four times higher than can be explained by models us-

Figure 1. Schematic diagram of BC/OC information flow, showing the possible source inconsistency between models and observations



ing present emission inventories (Streets et al. 2003). These measurements were conducted off the coasts of India and China.

As figure 1 illustrates, the problem may be attributable to inconsistencies between the laboratory measurement methods used to derive emission factors for combustion processes and the measurement techniques used to derive observed BC concentrations during field campaigns. It could also simply be a result of differences between thermal and optical techniques. Whatever the reason, it is clear that at present there is no consensus within the research community about emissions, modeling, and observations of BC. Therefore, more research is needed to better characterize BC and coordinate the representations of BC among different parts of the research community. Policy steps should, therefore, be formulated with caution until this has been done.

4. Black smoke and climate policy

Although the climate effects of black smoke are exerted at both global and regional levels, most of the work to date has focused on the global effects. When the Intergovernmental Panel on Climate Change (IPCC) issued its second assessment report about climate change (IPCC 1996), the treatment of radiative forcing of aerosols was rudimentary.[1] Qualitatively, the role of aerosols in the absorption of solar radiation was understood, but the magnitude of the forcing was unclear. In this 1996 report, the impact of soot in aerosols from fossil fuel emissions was estimated at 0.1 watts per square meter (W/m^2), within a range of 0.03 to 0.3. A separate estimate for particles associated with biomass burning was included in the report, however, and some fraction of these particles would be BC. A clear estimate of radiative forcing by particulate species was not attempted.

In the late 1990s, scientists began to realize that the physical form of BC particles in the atmosphere could have a dramatic influence on their radiative properties. Perhaps the most influential paper was by Jacobson (2001). On the basis of modeling the effects of BC in different types of mixtures, Jacobson showed that when BC was externally mixed with other aerosol particles its forcing could be as much as 0.62 W/m^2. This value was much higher than the prevailing IPCC value at that time (0.1 W/m^2). When he compared his BC values with the IPCC values of 0.47 W/m^2 for methane (CH_4) and 1.56 Wm^2 for CO_2, Jacobson concluded that after CO_2 (and subject to uncertainties) BC may be the second-most-important component of global warming in terms of direct forcing.

James Hansen and colleagues took up the banner of BC in a famous paper (Hansen et al. 2000). Assuming a radiative forcing of 0.5 W/m^2 for BC, they advocated a strategy of slowing global warming by reducing the emissions of primary aerosols such as BC, as well as non-CO_2 greenhouse gases. Hansen et al. further suggested that, if the World Bank were to support investment in modern technology and air quality control in India and China, the reductions in BC would not only improve local health and agricultural productivity, but would also benefit global air quality and climate. In a follow-up paper (Hansen and Sato 2001), the authors redrew the famous IPCC bar chart of climate forcings since preindustrial times (IPCC 1996, 2001) with an even higher value of 0.8 ($\pm$ 0.4) W/m^2 for BC.

Hansen's argument was criticized by some analysts (e.g., Smith, Wigley, and Edmonds 2000), who believed that it deflected attention away from CO_2, which Hansen never intended to do, and focused on short-term rather than long-term climate effects, which Hansen acknowledged. In fact, as Andreae (2001) observed in

1 Radiative forcing is the perturbation to the energy balance of the earth-atmosphere system, caused by a change in the concentration of an atmospheric gas or aerosol. A positive radiative forcing means a warming of the earth's surface, and a negative forcing means a cooling.

his review of Jacobson's 2001 paper in *Nature,* the short lifetime of BC is a possible advantage relative to the goal of rapid improvement of air quality: if we could somehow stop emitting BC today, it would be gone from the atmosphere in a week or two. Neither Hansen nor his critics fully appreciated the emission control implications of BC because they did not fully understand the contributions of various sources to total BC emissions. In fact, because a sizeable proportion of BC comes from the residential sector in developing countries, it is quite possible to target these sources preferentially. Such an environmental initiative would be fully consonant with social and economic goals to alleviate poverty and reduce rural/urban inequalities in China. One might liken the potential benefits to the great strides achieved through the rural electrification program in the United States in the 1930s.

The IPCC published its third assessment report in 2001 (IPCC 2001), emphasizing the importance of aerosols in influencing the radiation budget of the earth. Substantial progress was acknowledged in defining the direct effects of different aerosols; however, fossil-fuel BC aerosol was assigned a forcing of only 0.2 W/m^2, which was not in line with the latest works of Jacobson and Hansen.

Both Jacobson and Hansen have continued to publish papers on the importance of BC to global and regional climate modification. Jacobson (2002) advocated control of fossil-fuel BC (and organic matter) emissions as possibly the most effective method of slowing global warming. His model predicted that 20–45 percent of net warming could be eliminated within 3–5 years by eliminating all fossil-fuel BC and organic matter. This period is much shorter than the time estimated to achieve such a slowdown in global warming by achieving a similar percentage reduction in CO_2 emissions (50–200 years). Jacobson further suggested that diesel vehicles, though more energy efficient, might contribute more to warming than equivalent gasoline vehicles because of their higher particle emissions.

The profile of BC was further enhanced during this time by the results from the Indian Ocean Experiment (INDOEX). Lelieveld et al. (2001) reported very high concentrations of aerosols containing substantial amounts of BC (as high as 17 percent) over the Indian Ocean. The higher the BC content in such aerosols, the more sunlight is absorbed, which can lead to serious perturbations in the regional hydrological cycle and climate. These results were subsequently generalized in a paper by Ramanathan et al. (2001), in which carbonaceous aerosols were termed "a major wild card." They concluded that the effect of BC on local climates will depend on subtle details of how the surface and the atmosphere are coupled together. The INDOEX findings then gave birth to the so-called Asian Brown Cloud phenomenon (UNEP and C^4 2002), which emerged in the popular press during 2002.

Partly as an outgrowth of the INDOEX revelations and partly as a result of the new BC forcing estimates, the National Aerosol-Climate Interactions Program (NACIP) was developed in the United States to focus new research on aerosols and their interactions with the climate system. Three federal agencies—NASA, NSF, and EPA—sponsored a workshop and the preparation of a white paper by a NACIP scientific steering committee. This report was formally released on 9 May 2002 and drew three key conclusions:

- Aerosol effects on climate are the largest source of uncertainty in the current IPCC estimates of the global climate forcing that is attributable to human activities.
- Recent observations that raise the possibility that aerosols have substantive impacts on the regional climate in some parts of the world make the need for the NACIP even more imperative.
- Our present understanding of aerosols is insufficient to quantify their influence on global and regional climate change. A substantial effort, with new research based on field observations (using regional aerosol observatories, exploratory aircraft flights, satellite instrumentation, and multiplatform field campaigns), is required to achieve the necessary understanding.

The high profile of this white paper and the support of three government agencies made an impression on the Bush administration. The importance of aerosols was further enhanced by the personal testimony of James Hansen to both the U.S. Senate and the White House. Soon after taking office, President George W. Bush repudiated the Kyoto Protocol, and this policy stance was affirmed in the Rose Garden speech of 11 June 2001. Clearly influenced by aerosol advocacy, President Bush criticized the Kyoto Protocol as flawed because it failed to address two major pollutants that have an impact on warming and are proven health hazards: black soot and tropospheric ozone. He observed that reducing emissions of both species would not only address climate change, but also dramatically improve people's health. A skeptic might have wondered whether this statement was truly a call for action on soot and ozone or merely an excuse for inaction on CO_2.

In the same speech, President Bush announced a new U.S. initiative on climate change science and technology. This culminated in the release on 14 February 2002 of a new U.S. climate change strategy, which included, among other elements, a climate change research initiative (CCRI) under which the United States would spend US$1.7 billion in FY2003 for basic research on climate change, US$40 million of which would be dedicated to leverage other funding to address major gaps in our understanding of the carbon cycle and the role of black soot. A specific priority for FY2003 was to develop reliable representations of the global and regional climatic forcing by atmospheric aerosols. CCRI investments would implement the NACIP plan to define and evaluate the role of aerosols that absorb solar radiation, such as BC and mineral dust. Proposed activities would include field campaigns (including aircraft flyovers), in situ monitoring stations, and development of improved modeling and satellite data algorithms. In this way, aerosols became a formal part of U.S. policy planning and scientific research.

The commitment of the government was strengthened by congressional testimony on 10 July 2002 by James Mahoney, the new Assistant Secretary of Commerce for Oceans and Atmosphere and Director of the Climate Change Science Program. A key avenue of future scientific inquiry was stated to be the relative importance of carbon-based (BC) aerosols, sulfate-based aerosols, and CO_2 and other greenhouse gases in influencing climate change. Mahoney stressed that each of these species was related to differing control strategies. This is an important point, because, not only might different control strategies be needed for each species, but *any* control strategy will potentially affect the emissions of *many* species. This is particularly critical for strategies that would involve a reduction in coal use, which would reduce emissions of many climate-modifying species at the same time (e.g., CO_2, SO_2, BC, CH_4, and hydrocarbons). The net effect can be perverse, as discussed in section 5.

On 27 November 2002, John Marburger, director of the White House Office of Science and Technology, said at a news conference that the United States might put more stress on controlling carbon soot as a speedy way to respond to global warming. Marburger used carbon soot as an example of how the United States could take action while still refining its overall plan on climate change. Although it could take as long as 5 years to gather the information required for the development of optimal strategies to address climate change, action could be taken in the interim, and carbon soot is a substance that could be controlled fairly quickly. Like many other issues, however, climate change mitigation has languished during the past 3 years. The Secretary of Energy at that time published a paper summarizing the Bush Administration’s approach to climate change, but it focused only on new technology initiatives such as carbon sequestration, hydrogen fuel, clean coal, and various voluntary and incentive measures (Abraham 2004). No further mention of BC mitigation in the United States has been forthcoming.

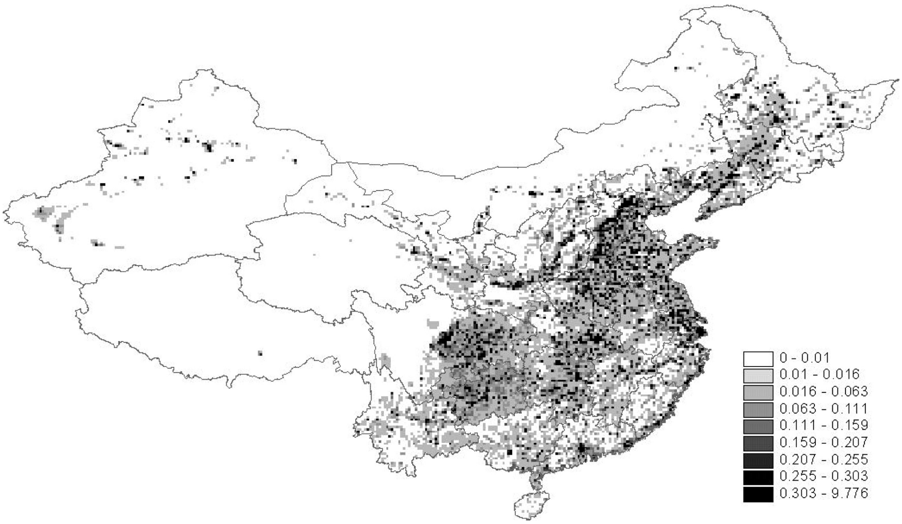
5. Impacts and options for China

It should be clear from the preceding discussion that China is the country with the most to lose from high emissions of BC and the most to gain from reduction of BC emissions. The uncontrolled combustion of carbonaceous fuels (mainly coal and biofuels) in homes and small industrial enterprises is the main cause of high emissions of BC in China. Inhalation of fine particles in the immediate vicinity of these sources undoubtedly causes severe health problems, though they have been difficult to quantify. People in China and other developing countries are exposed to smoke from cookstoves for 3–7 hours daily and more in the winter months in northern regions, when homes must also be heated. Women and children, who spend more time in the indoor environment, are at greater risk. Smoke from biofuels is believed to pose the greatest health threat. Higher risk of acute respiratory infections, tuberculosis, lung cancer, and blindness has been associated with indoor fuel consumption. It has been estimated that there are 2 million premature deaths annually from the household use of solid fuels worldwide.

Figure 2 shows the spatial distribution of BC emissions in China during 1995. Because BC is preferentially emitted from coal and biofuel combustion in the domestic sector, its emissions are concentrated in a curving west-to-east swath across the agricultural heartland of China, from Sichuan Province to Hebei Province. This is the region of China where both coal and agricultural residues are available to provide energy resources to a large and relatively poor rural population. This can be contrasted with the distribution of other pollutant species such as SO_2 and NO_x, which are primarily emitted in the industrial, power, and transport sectors. Thus, these emissions are concentrated around the populated and industrial centers of China—that is, the coastal provinces from Guangdong to Liaoning (see Arndt et al. 1997; van Aardenne et al. 1999; Streets et al. 1999). One message, therefore, is that strategies for BC reduction must target particular geographical regions, as well as specific source types.

Hansen's group has modeled the regional climate effects of BC in China on the assumption that there is a high concentration of absorbing aerosols over the country (Menon et al. 2002). They find that the aerosols heat the air locally, alter regional atmospheric stability and vertical motions, and affect the large-scale air circulation and hydrological cycle. On the basis of their climate model results, they hypothesize that this may be the cause of increased summer floods in southern China in recent decades, increased drought in northern China, and moderate cooling throughout China, while the rest of the world has been warming. Zhai and Pan (2003) analyzed the record of temperature extremes in China during the period 1951–99, using data from 200 weather stations. They observed the following: (1) a slightly decreasing trend in the number of hot days (>35°C), (2) a significant decreasing trend in the number of frost days, (3) increasing trends in the frequencies of warm days and warm nights, (4) a decreasing trend in the frequency of cool days, and (5) a strongly decreasing trend in the frequency of cool nights. Zhai and Pan hypothesized that

Figure 2. Spacial distribution of black carbon emissions in 1995 (10 min × 10 min resolution, unit = Gg/year)



these changes are the result of modifications to the regional climate from aerosol emissions.

The economic impacts of continued emissions of black smoke are probably very large, though they have yet to be calculated. The economic damage resulting from the effects on health caused by air pollution in China is known to be high and can greatly exceed (by a factor of 1–15) the costs of controlling harmful emissions (Li et al. 2004). The ecological effects of black smoke on crop production must also be high, though, again, such impacts have not been quantified. The effects of long-term climate modification could have profound economic effects, influencing many aspects of the social fabric of China.

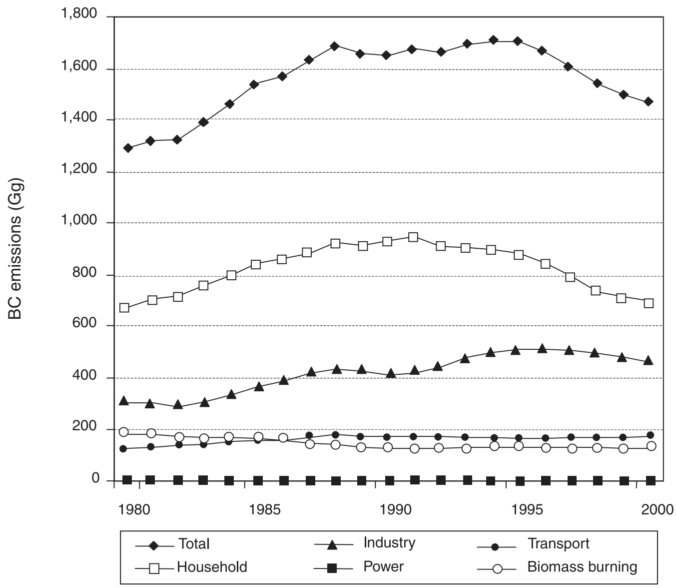
One obvious remediation strategy is to phase out the direct burning of solid carbonaceous fuels in small-scale operations. In China, this means eliminating the burning of raw coal in small, inefficient combustors (e.g., cookstoves, heaters, ovens, and kilns). China is taking steps to do this in the major cities, but the case for extending this policy to other cities, towns, and rural areas is strong. In terms of particulate emissions, switching from raw coal to coal briquettes is highly beneficial: Bond et al. (2002) have shown that almost no residual airborne PM is produced from the burning of Chinese coal briquettes. Coal washing for industrial applications can also bring major benefits quickly and relatively inexpensively.

In China, the elimination of biofuel combustion is another pressing matter. Ascending the energy ladder (a term coined by Kirk Smith) toward cleaner fuels—such as liquefied petroleum gas, biogas, natural gas, and electricity—in the domestic sector should be an urgent priority. This is already a social development goal for countries such as China, so environmental concerns provide an added impetus. Some of this work is already under way. For example, improved cookstoves have been distributed widely in China (Smith et al. 1993), and the government has mandated that coal-fired boilers in Beijing and other major cities be switched to other heat sources that use cleaner fuels. One concern is that the driving force for improved stoves is usually fuel efficiency, to reduce the amount of fuel used to deliver a given amount of useful energy. In pursuit of more efficient heat transfer, however, combustion efficiency might be sacrificed, leading to greater production of particles and partially oxidized carbonaceous gases. For example, Zhang et al. (1999) found higher emission rates for improved stoves compared with those of traditional stoves. Future designs for improved stoves should concurrently optimize energy and environmental performance.

Open biomass burning contributes significantly to global BC production, and in Asia it is particularly high, producing an estimated 18 percent of total Asian BC emissions (Streets et al. 2003). There is no good estimate of the amount of burning that occurs in China. Steps can be taken to minimize open burning of vegetation in China. The burning of agricultural residues in fields after harvest has been banned throughout the developed world. In some Chinese provinces, however, it remains common practice, whereas in others it is officially banned but tolerated. Alternative strategies for farmers to dispose of agricultural residues need to be aggressively adopted. Biogas production is one attractive alternative, and biofuel/additive briquettes are being studied in Sichuan Province. Plowing under the crop residues after harvesting is a simple preventative step (though one must remember that one reason for burning is elimination of pests that have taken hold during the growing season).

In the transportation sector, modern gasoline-fueled vehicles have very low particulate emissions, and therefore emission controls are not necessary. Diesel vehicles, on the other hand, generate significant amounts of fine particles and BC. Vehicle particulate emission standards in the United States and other developed countries are being tightened, and consequently diesel vehicles in these countries will need particulate controls. Vehicle emission standards in China, however, are generally far behind

Figure 3. Trends in China's black carbon emissions, 1980–2000, by sector



Western standards, even though good progress is being made in a few of the most modern cities. It is not clear whether diesel vehicles will be subject to stringent standards in the near future, and, even if they are, it would take a long time for new vehicles to penetrate the in-use vehicle fleet. In China, we must also acknowledge the existence of very many old, poor-quality vehicles that generate high levels of fine particles. Unconventional vehicles that serve the dual purposes of field plowing and goods transportation are widespread in the countryside. For all these reasons, upgrading the vehicle fleet in China would reduce BC and OC emissions and ease the burden of regional carbonaceous aerosols.

Trends in BC emissions in China over 1980–2000 (Streets and Aunan 2005) indicate that some of these transitions are already under way (figure 3). We estimate that BC emissions have been slowly declining since 1995, as coal begins to exit the household economy (since 1991) and environmental controls have penetrated the industrial economy (since 1996). Coal use in the power sector continues to increase but generates little BC. Transportation-related BC is gaining ground but from a low base. Continued vigilance is required, however, to keep particulate emissions in check in the face of rapid economic growth. In contrast to BC emissions, CO_2 and

NO_x emissions continue to increase, whereas SO_2 emissions are hard-pressed to remain level. Technological progress and socioeconomic development are the two keys to reducing BC emissions.

Simultaneously reducing the emissions of several species produces rather perverse climate effects. Streets et al. (2001b) examined the reduction in coal use in China that occurred during the late 1990s. This trend simultaneously reduced China's emissions of CO_2, SO_2, CH_4, and BC, all of which have effects on radiative forcing. The climate effects of these reductions were simulated within the Jacobson model. The net effect of the emission reductions was an *increase* in global mean temperatures over a 100-year period. This is attributable to the dominant effect of SO_2 as a cooling agent in the atmosphere in the form of sulfate (SO_4) aerosol (temperature change from SO_4 emission reduction $= +0.040°K$), though it is clear that the accompanying reduction in BC emissions partially offsets the effects of the SO_2 reductions (temperature change from BC emission reduction $= -0.026°K$). Both aerosol influences heavily outweigh the temperature effects of the changes in gas concentrations ($CO_2 = -0.003°K$; $CH_4 = +0.001°K$). Thus, BC emission reductions can play a significant role in mitigating global climate change. Effects at the regional level would be even more pronounced.

6. Conclusion: A new paradigm for global climate change protocols?

The addition of BC-reducing measures to global climate change mitigation agreements such as the Kyoto Protocol offers an opportunity to fully engage China and other developing countries that have thus far resisted efforts to convince them to reduce greenhouse-gas emissions. A new compact might have the following attributes:

The United States and Europe (and other developed countries) reduce CO_2 emissions, because

- They are the cause of most of the accumulated CO_2,
- They can (arguably) afford the more expensive measures of CO_2 control,
- They will accrue ancillary energy security benefits, and
- They can contribute a long-term solution.

China and other developing countries reduce BC emissions, because

- They are the cause of most of the emitted BC,
- They can (arguably) afford the less expensive measures of BC control,

- They will accrue ancillary health benefits, and
- They can contribute a short-term solution.

It is clear that the effects of carbonaceous particles in the atmosphere are becoming increasingly important from many different perspectives. By incorporating measures to reduce such emissions into a climate agreement a number of co-benefits can be achieved, perhaps not the least of them being the development of a true global compact in which *all* countries play a role, each according to its means, in mitigating the effects of climate change. This can also serve to focus development aid more sharply toward reducing the effects of those energy sources that generate fine particles. Lending agencies will find impetus to consolidate development, health, and climate change goals.

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