Testimony for “Clearing the Smoke: Black Carbon Pollution”

House Committee on Energy Independence and Global Warming

United States House of Representatives

The Honorable Edward Markey, Chair

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Tami C. Bond, Associate Professor

University of Illinois at Urbana-Champaign

Chairman Markey and Ranking Member Sensenbrenner, and members of the Committee, thank you for this opportunity to discuss black carbon, its origins, and its role in climate change. I am honored to participate in your committee's important discussions on climate change, energy use, and a wide variety of solutions.

I am Tami Bond, Associate Professor of Civil and Environmental Engineering at the University of Illinois, Urbana-Champaign. I began measuring black carbon 15 years ago, when I traveled to the former East Germany, an economy in transition, to measure a small coal boiler with few emission controls. Since that time, I've measured diesel engines and cookstoves, and created estimates of emission rates that are used in global atmospheric models. I am currently co-leading a group of about 30 scientists conducting a scientific assessment of the net impact of black carbon on the climate system. My comments to you are based on that experience.

1. Scope of testimony

In this document, I will discuss:

- the nature of black carbon
- black carbon's impact on the Earth's radiative balance
- reducing black carbon compared with reducing carbon dioxide
- sources that emit black carbon, both globally and in the United States
- research remaining to evaluate black carbon mitigation

2. What is black carbon?

Smoke has been intimately associated with civilization for millennia, with home heating for centuries, and with industrial production since the invention of the steam engine. Black carbon is a component of this smoke, responsible for its dark appearance. Upon inspection under an electron microscope, black carbon looks very different than other particles: it is a collection of tiny spheres, like a bunch of dark grapes.

Some of the unique physical properties of black carbon also give it interesting behavior in the environment. It has a high surface area: one ounce of black carbon dispersed in the atmosphere blocks the amount of sunlight that would fall on a tennis court. The "black" in the name of this substance means that it absorbs every color of light; it does so because it is chemically similar to graphite. This absorbed light is turned into heat and transferred to the atmosphere.

Because black carbon is so good at absorbing sunlight and turning it into heat, emitting one-third of an ounce to the atmosphere (about the weight of two nickels) is like adding a home furnace, running continuously, to the Earth system for one week. That amount would be emitted by burning about three gallons of fuel in a diesel engine without advanced controls.[i]

3. Black carbon is a strong climate warmer

The contribution of any pollutant to warming or cooling the climate is often expressed as "forcing," or the change in heat input caused by that pollutant at the top of the atmosphere. In 2007, the Intergovernmental Panel on Climate Change (IPCC) estimated the forcing of black carbon as +0.34 watts per square meter (W/m^2) [1]. This estimate was based on several models of the global atmosphere. It can be compared with the forcing of carbon dioxide, which was estimated as +1.66 W/m^2 in the same document. Black carbon's forcing is smaller but significant.

Criticisms could be made of the model results summarized in the IPCC report. Many of them did not include a well-understood change which would make the radiative forcing higher. Black carbon collides and interacts with other particles, so that each particle contains many chemicals, not just black carbon. This mixing increases the absorption of black carbon by about 50%. The change is not controversial; it has been measured both in laboratory tests and in field measurements [2,3]. This makes the forcing per emitted mass much higher than most models predict.

Including the mixing, my best guess of black carbon atmospheric radiative impact for an emission rate of 8.2 million tons (7.5 million metric tons, or the estimated emission rate in 2000) is about +0.46 watts per square meter[ii]. Forcing by black carbon on snow is an additional +0.05 W/m^2. This apparently small snow forcing is highly effective at producing warming [4].

The emission rate of black carbon is another important factor in determining its forcing. Forcing is directly proportional to emission rate, so if emission estimates are doubled, the forcing estimate will double as well. Atmospheric measurements suggest that our current estimate of year 2000 emissions is too low in some regions [5]. Forcing estimates as high

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[i] The values I used for this calculation are: normalized direct radiative forcing = 1800 watts per gram, resulting in a heat input of about 17 kW or 58000 Btu/hour. The diesel engine is assumed to have an emission rate of 1 gram BC per kg of fuel, similar to engines with early but not stringent regulations.

[ii] "Atmospheric radiative impact" is similar to forcing, except that it refers to all the material in the atmosphere, not the difference between present day and 1750. IPCC's estimate of atmospheric radiative impact would have been similar to this one. Because emissions in 1750 are poorly known, and because all present-day emissions could be considered for mitigation, I prefer to present the total impact rather than subtracting a pre-industrial baseline. Models summarized by IPCC did not include the mixing effect in some models, but did include some models with high emissions.

as 1 watt per square meter [6,7] have been published and are usually associated with models that assume more black carbon in the atmosphere than other models.

Besides the emission rate, there are other sources of uncertainty in the forcing estimate. Some of these factors include rainout rates and whether black carbon is suspended above or below clouds. These factors lead to an additional uncertainty of about 50% in forcing estimates.

Work to resolve the magnitude of emissions and the resulting forcing remains. Nevertheless, we have high confidence that **atmospheric and snow forcing by black carbon leads to warming and is significant in comparison with greenhouse gases.** (As discussed in Section 5, however, the impacts of individual emission sources may not be warming.)

4. The atmosphere responds rapidly to changes in black carbon emissions

Black carbon, and other particles, stay in the atmosphere for only about a week. They are rapidly removed by rainfall. Even during those few days, it can travel for thousands of kilometers, reaching other continents and traveling to sensitive regions such as the Arctic. However, the short lifetime gives it a very different character than carbon dioxide.

If emissions of black carbon are shut off, its warming will be stopped within a few days. This makes it a powerful tool to address warming quickly. This is also true of other short-lived climate forcers such as ozone.

Black carbon does not accumulate in the atmosphere, while carbon dioxide does. If both CO_2 and black carbon emissions remain constant, in a few decades, there will be a lot more CO_2 in the atmosphere than there is today, but the same amount of black carbon. This means that CO_2 requires long-term management, which your committee is discussing elsewhere. It also means that reducing black carbon emissions is not a long-term solution to climate change. It is, however, a component of our current toolbox.

Reducing black carbon and ozone in the atmosphere is like applying an emergency brake in a car out of control. It will slow the vehicle quickly and give you a little time to think. But the problem will continue if you don't take your foot off the gas pedal—that is, if CO_2 emissions are maintained.

One way to compare the warming of pollutants is to add up (integrate) the energy added to the atmosphere over some period of time and compare it with the energy added during the same period by CO_2. The ratio between the two is known as the *global warming potential*. In current discussions about climate mitigation, 100 years is the chosen integration time. For this time period, black carbon has a global warming potential of about 700. That is, even during its few days in the atmosphere, one pound of black carbon absorbs 700 times as much energy as one pound of emitted CO_2.

Although black carbon has a powerful impact, its emissions are over one thousand times smaller than the amount of fuel carbon turned into carbon dioxide each year. Thus, both are important-- black carbon due to its strong warming, and carbon dioxide due to its abundance and long lifetime.

5. Black carbon does not travel alone

Sources that emit black carbon also emit several other pollutants. These include sulfur dioxide, which leads to sulfate particles, and carbon particles that are not black, known as "organic" carbon. These pollutants generally reflect light away from the Earth; this causes them to cool the Earth system. Gases that affect ozone and methane are also emitted with the particles, usually adding some warming.

Any action to reduce black carbon will also affect any *co-emitted pollutants* from the same source. Any emission source produces warming pollutants (black carbon and some gases) and cooling pollutants (sulfates and organic carbon), and the result is like mixing hot and cold water in a faucet. The mixed water can be very warm, very cold, or in between depending on the amount of each flow. Sources with high emissions of warming pollutants are the most promising targets for reducing black carbon warming.

The warming by black carbon may also be offset by some other interactions in the atmosphere, especially those involving clouds. Removing particles from clouds may result in bigger droplets, clouds that are less bright, less reflected energy, and therefore a warmer Earth. This is one of the major uncertainties in quantifying the link between black carbon emissions and climate benefit.

6. Sources and magnitudes of black carbon emissions

Estimates of black carbon emissions in 2000, based on *bottom-up* calculations, were about 5.4 million tons (4.9 million metric tons) from energy-related sources including fossil and biofuel burning, and about 2.9 million tons (2.6 million metric tons) from open burning of biomass. The total of about 8.2 million tons is the one used for the forcing estimates in Section 3. Later, I'll explain some of the limitations of "bottom-up" emission estimates.

Figure 1 summarizes the main source categories: (1) diesel engines for transportation or industrial use; (2) residential solid fuels such as wood and coal, burned with traditional technologies; (3) open forest and savanna burning, both natural and initiated by humans for land clearing; and (4) industrial combustion, usually in smaller boilers. Although the estimates given here have some uncertainty, we have confidence that the major types of contributors to black carbon emissions have been identified. As estimates improve, the magnitude of each sectoral contribution may change somewhat.

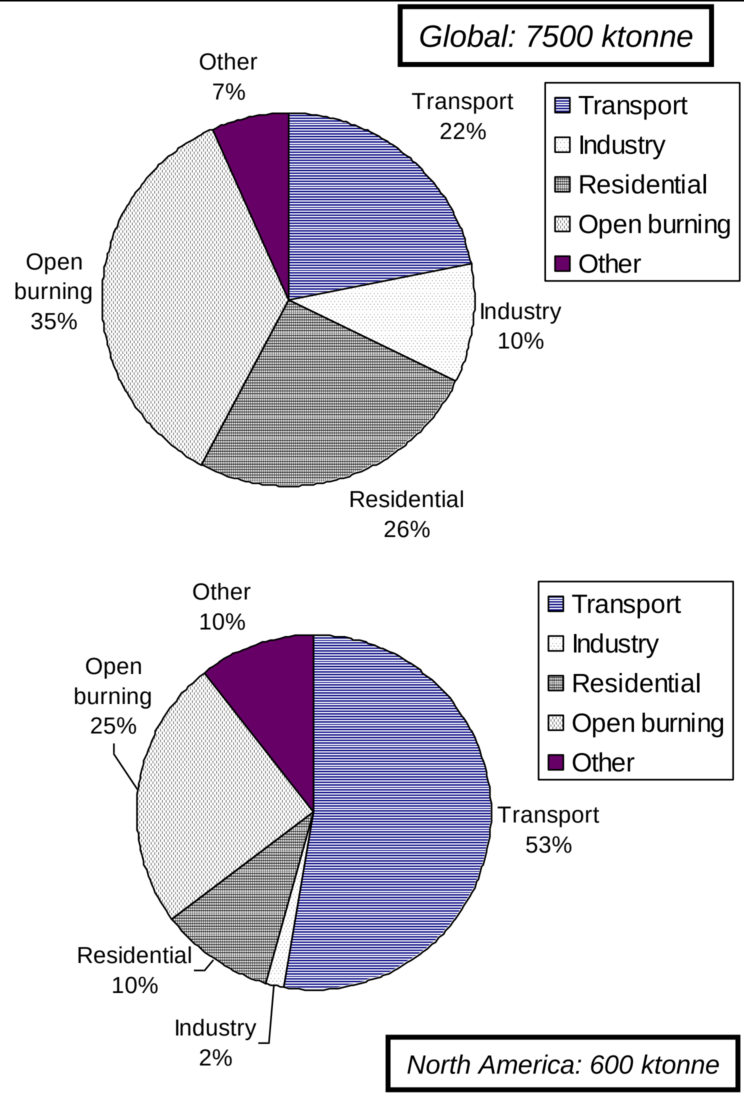

Figure 1. Global and North American sources of black carbon. Open burning is largely in the forests of Canada. 1 ktonne (metric)= 1100 tons.

Emissions in North America are quite different than the global average. Transportation contributes a much greater fraction, and residential fuels a much smaller fraction. Total emissions are also a small fraction of the global total, although per-capita emissions are within a factor of three for all regions.

The history of the United States illustrates how black carbon emitted from energy use changes with development [8]. In the late 1800s, U.S. black carbon emissions were dominated by residential solid fuel, especially coal. Industry was on the increase, too. Making the coke needed to feed the steel furnaces of Pittsburgh created a lot of black carbon,. Black carbon emissions decreased greatly when companies started capturing the gases from coke ovens. The invention of boilers that burned pulverized (powdered) coal rather than piling the fuel on a grate allowed black carbon emissions in the United States to decrease (Figure 2) despite phenomenal growth in coal use. Eventually, industrial pollution became relatively clean, in part due to regulations that come into play in a richer society, and in part due to technology. However, a wealthy society also has greater mechanization and transport of goods, leading to a greater use of diesel engines. This North American emission trend [2,9] is consistent with ice-core records in the Arctic [10].

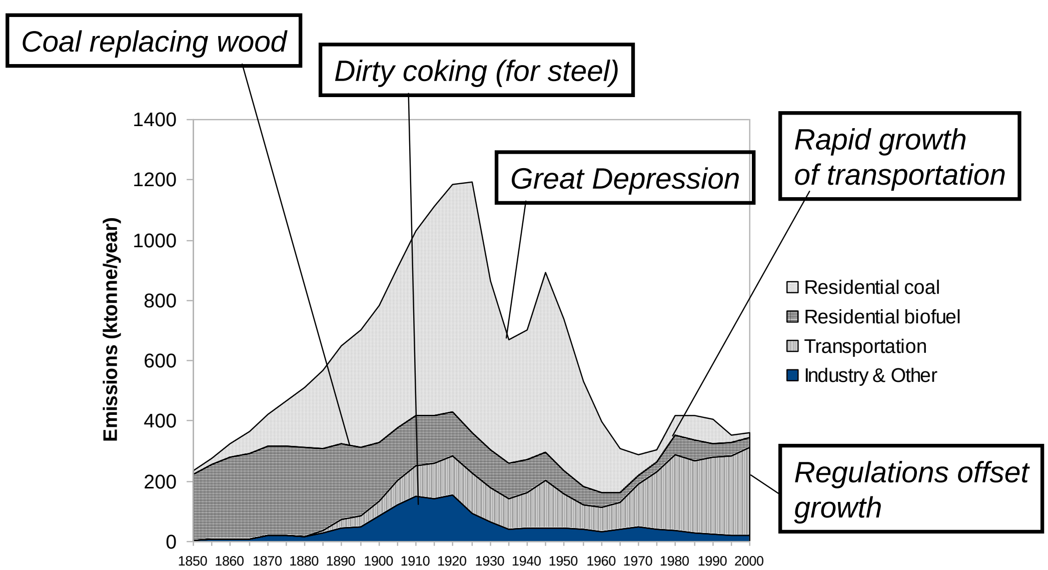

Figure 2. History of emissions for the United States, demonstrating transitions between fuels and dominant emitters (early 20th century), and the success of regulation at offsetting high growth due to emissions (late 20th century).

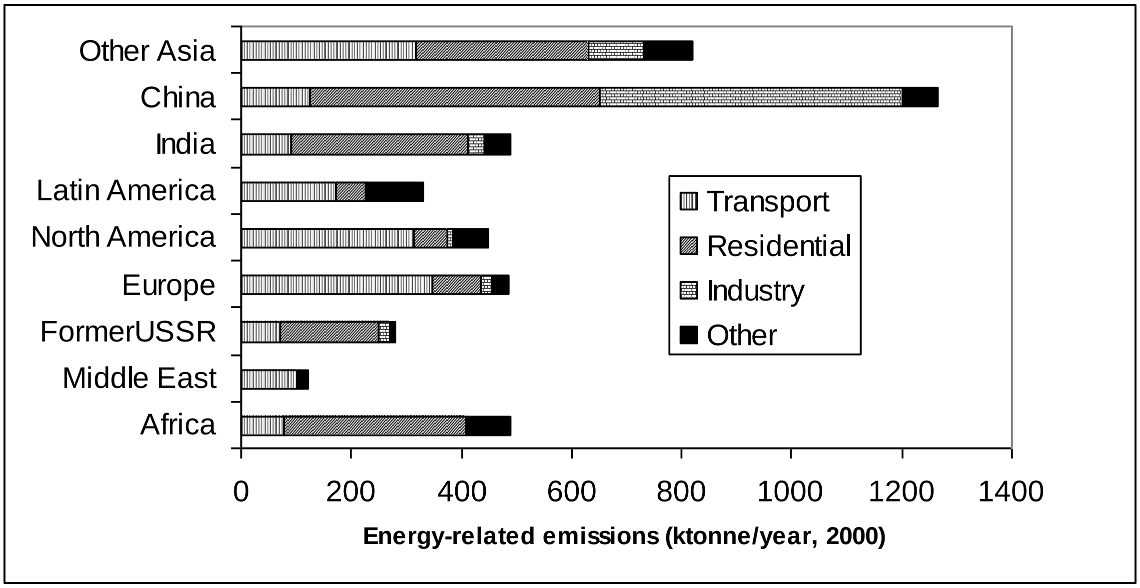

Figure 3. Black carbon emissions by type and world region, for energy-related emissions only (i.e. excluding open burning).

As development occurs, per-capita emissions of black carbon change a little, but the sources change quite a lot [11]. This source shift is apparent in emission differences between world regions, as well (Figure 3). In countries where infrastructure is limited and clean fuels are unavailable or unaffordable, black carbon emissions come mainly from solid fuels for heating and cooking. Regions with large populations and poor infrastructure have high black carbon emissions from residential fuels. These emissions have a large atmospheric impact, but also a large potential for cleaning up. In highly developed regions like the United States and Europe, the main sources are diesel engines.

Of the sources discussed above, **diesel engines** are the richest in warming black carbon pollutants, by far. **Residential cooking and heating** emissions have some organic carbon and, in some cases, sulfate precursors. Their net effect on sunlight is probably still warming, but their interaction with clouds is unknown. **Open burning of biomass** has the largest fraction of co-emitted organic carbon (cooling) pollutants. Finally, there is very little information on small industrial sources, and measurements of co-emitted pollutants are needed in order to determine whether they have more warming or more cooling pollutants.

While there are still substantial black carbon emissions in the U.S., it is not the major contributor to global BC emissions. New diesel regulations, retrofit programs, and implementation of advanced diesel technology will ensure that black carbon emissions decline even if fuel consumption grows.

The history of the United States also shows that given proper conditions and incentives, many polluting technologies can be quickly phased out. For domestic cooking, especially in developing countries, health and convenience will drive such a transition when affordable, reliable alternatives that are consistent with local cooking practices are available. For other sources, such as vehicles or coal boilers, regulations may be required to facilitate either the development of new technology or the transition to existing technology. Collaboration and technology transfer can assist in ameliorating black carbon emissions elsewhere in the world, and many regions can also benefit from the lessons learned in reducing road-transport emissions.

The discussion above focused on black carbon from energy consumption, not emissions from open burning of biomass. Open burning is a large contributor to emissions in regions with large forests or grasslands. Much of that open burning is natural, but some is generated by humans. Burning of farmland before or after harvest can also contribute to pollution in some regions. There are fewer acceptable alternatives for open burning than for energy-related burning.

7. Remaining research

My testimony has mentioned some of the uncertainties in the science surrounding black carbon. To confirm that mitigating sources rich in black carbon will in fact benefit climate, a few questions must be addressed:

- What is the net effect of cleaning up emission sources on the Earth's radiative balance, considering all co-emitted pollutants?
- How do clouds respond to changes in emissions of particles of different composition?
- How does atmospheric heating by black carbon affect clouds?
- How does black carbon deposition affect snow?
- How do these impacts vary among world regions?
- What is our best guess of uncertainty in all of these impacts?

Fortunately, a co-ordinated study, entitled "Bounding the Role of Black Carbon in Climate," is underway to assess the questions above. The study is sponsored by the Atmospheric Chemistry and Climate initiative, with support from the International Global Atmospheric Chemistry organization. I and three other scientists are leading the group of about thirty co-authors, and I expect a product in June, 2010 to be submitted as a peer-refereed journal paper.

Although we certainly do not expect the science of black carbon to be solved by June, the report will contain our best current guess of net black carbon impact on climate, with uncertainties. The report will also detail any key remaining uncertainties that must be addressed in order to fully evaluate the promise of black carbon mitigation.

References

[1] Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betta, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, Changes in atmospheric constituents and in radiative forcing, in *Climate change 2007: The physical science basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tigor, and H.L. Miller, pp. 129-234, Cambridge University Press, Cambridge, UK, 2007.

[2] Schnaiter, M., C. Linke, O. Möhler, K.-H. Naumann, H. Saathoff, R. Wagner, U. Schurath, and B. Wehner (2005), Absorption amplification of black carbon internally mixed with secondary organic aerosol, *J. Geophys. Res.*, *110*, D19204, doi:10.1029/2005JD006046.

[3] Moffet, R.C., and K.A. Prather (2009), In-situ measurements of the mixing state and optical properties of soot with implications for radiative forcing estimates, *Proc. Natl. Acad. Sci.*, *106* (29), 11872-11877.

[4] Flanner, M.G., C. S. Zender, J. T. Randerson, and P.J. Rasch (2007), Present-day climate forcing and response from black carbon in snow, *Journal of Geophysical Research*, *112*, D11202, doi:10.1029/2006JD008003.

[5] D. Koch, *et al.* Evaluation of black carbon estimations in global aerosol models, Atmospheric Chemistry and Physics 9 (9001-9026), 2009.

[6] Sato, M., J. Hansen, D. Koch, A. Lacis, R. Ruedy, O. Dubovik, B. Holben, M. Chin, and T. Novakov (2003), Global atmospheric black carbon inferred from AERONET, *Proc. Natl. Acad. Sci.*, *100* (11), 6319-6324.

[7] Ramanathan, V., and G. Carmichael (2008), Global and regional climate changes due to black carbon, *Nature Geoscience*, *1*, 221-227.

[8] Bond, T.C., E. Bhardwaj, R. Dong, R. Jogani, S. Jung, C. Roden, D.G. Streets, S. Fernandes, and N. Trautmann (2007), Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000, *Glob. Biogeochem. Cyc.*, *21*, GB2018, doi:10.1029/2006GB002840.

[9] Novakov, T., V. Ramanathan, J.E. Hansen, T.W. Kirchstetter, M. Sato, J.E. Sinton, and J.A. Sathaye (2003), Large historical changes of fossil-fuel black carbon aerosols, *Geophysical Research Letters*, *30* (6), 1324, doi:10.1029/2002GL016345.

[10] McConnell, J.R., R. Edwards, G.L. Kok, M.G. Flanner, C.S. Zender, E.S. Saltzman, J.R. Banta, D.R. Pasteris, M.M. Carter, and J.D.W. Kahl (2007), 20th-Century industrial black carbon emissions altered Arctic climate forcing, *Science*, *317*, 1381-1384.

[11] Bond, T.C. (2007), Can warming particles enter global climate discussions?, *Env. Res. Let.*, *2*, 045030.