Written testimony to the Oversight and Government Reform Committee
United States House of Representatives
October 18, 2007

Arctic Climate Effects of Black Carbon

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Abstract

The Arctic is warming about twice as rapidly as the rest of Earth. Black carbon (BC) particles are an important short-lived pollutant that explain a significant fraction of the observed Arctic warming. Most Arctic BC comes from fuel-combustion not from open fires. Arctic climate is very sensitive to the surface warming that BC causes. BC appears to warm the Arctic more than any other agent except CO_2. Reducing the concentration of Arctic BC now will cool the planet more than a delayed reduction.

Written Testimony

My name is Charlie Zender and I am an Associate Professor of Earth System Science at the University of California, Irvine. In that capacity I perform government-funded research on the roles of Black Carbon (BC) and other aerosols on global climate and, in particular, on the Arctic region. I am currently on sabbatical leave at the Laboratoire de Glaciologie et Géophysique in France conducting laboratory experiments on snow as part of International Polar Year activities. This committee requested that I testify regarding the effects of black carbon on Arctic climate. I thank Chairman Waxman, Mr. Davis, and the members and staff of the committee for this opportunity.

The Arctic is warming about twice as rapidly as the rest of Earth (*ACIA*, 2005). Although long-lived man-made greenhouse gases (GHGs) are the dominant cause of Earth's recent warming (*IPCC*, 2007), black carbon (BC) particles and other short-lived pollutants explain a significant fraction of the observed Arctic warming (*Flanner et al.*, 2007; *Quinn et al.*, 2007). Man-made BC has many attributes that make it a logical target for mitigation strategies that aim to decelerate near-term global warming (*Jacobson*, 2002, 2004), and Arctic warming in particular. Such policies can only complement, not replace, the longer term, GHG-oriented mitigation policies that are required to stabilize planetary temperatures.

My colleagues on this panel will describe what BC is, where it comes from, and how effectively BC reductions could slow down near-term global warming. My testimony describes four important aspects of BC effects on Arctic climate:

1. Most Arctic BC comes from fuel-combustion not from open fires.
2. Arctic climate is very sensitive to the surface warming that BC causes.
3. BC appears to warm the Arctic more than any other agent except CO_2.
4. Reducing Arctic BC now will cool the planet more than a delayed reduction.

Sources

Many of us grew up thinking of black carbon, also called soot, as the harmless smudges Santa Claus acquired sliding down our chimneys, and not as an environmentally harmful pollutant. So it can be disconcerting to learn that BC describes an agglomeration of carbonaceous particulates that form and are emitted (along with carbon dioxide) as combustion by-products from smokestacks, tail-pipes, forest fires, and humble cooking stoves.

Black carbon is generated by combustion of fossil-fuel (e.g., coal, oil, gasoline), bio-fuel (e.g., wood for stoves and heating), and open biomass burning (e.g., forest fires). Humans are responsible for fossil- and bio-fuel emissions. Biomass burning includes natural (e.g., lightning-sparked fires) and anthropogenic (e.g., agricultural, land-clearing fires) components in uncertain proportions. In most years, 70–90% of Arctic BC appears to stem from fuel combustion (*Koch and Hansen*, 2005; *Flanner et al.*, 2007). Year-to-year variability in fire conditions and transport paths lead to a considerable range in the biomass burning contribution, which may reach 50% in very strong boreal fire years (e.g., 1998).

Other combustion by-products include organic matter (sometimes called organic carbon) and inorganic aerosols (e.g., sulfate) that are highly reflective and so can have climate effects that differ from, and sometimes compete with, BC. Strategies to reduce BC must consider the effects on other combustion-derived aerosols since their sources are inextricably linked. The reflective aerosols produced by combustion have a smaller contrast with bright Arctic surfaces than does BC. To first order, this contrast causes BC to dominate the net effect of combustion-derived aerosols on the Arctic. It also explains why BC will become a less efficient warming agent in the Arctic as snow and ice surfaces there continue to warm, melt, darken, and thus to lose contrast with BC.

Unlike CO_2, an inert gas that remains in the atmosphere for many decades, BC is a particulate and deposits to the surface within about a week of its emission. During this week, a BC particle has good chance of circulating to the roughly 20% of the northern hemisphere that is seasonally or "permanently" snow and ice-covered, including Alaska, Greenland, and the Arctic Ocean. Twenty years of light absorption measurement from Barrow, Alaska, show the seasonality of Arctic BC superimposed on longer term trends (Figure 1).

Presently the vast majority of Arctic BC originates outside the Arctic. Emissions inventories, climate models, meteorological back-trajectories, and *in situ* samples confirm that most Arctic BC originates as fuel combustion by-products, primarily from the northern hemisphere mid-latitudes, followed by South Asia in importance (*Bond et al.*, 2004; *Koch and Hansen*, 2005; *McConnell et al.*, 2007; *Quinn et al.*, 2007). Biomass burning emissions and transport paths vary from year-to-year. Forest fires in North America and Siberia may contribute up to 30% of Arctic BC in years of exceptionally strong burning (e.g., 1998) (*Flanner et al.*, 2007).

Economic and technological factors clearly affect Arctic BC concentrations. The long term trends of BC in some Arctic locations can be obtained from ice cores. From 1880–1950, industrial emissions increased BC concentrations in Greenland snow seven-fold relative to pre-industrial levels (*McConnell et al.*, 2007) (Figure 2). BC concentrations in Greenland have been lower since about 1950, likely due to the shift to oil, gas, and cleaner coal burning in North America and to wildfire suppression. BC decreased in some Arctic regions in the late 1980s and early 1990s during the decline of industrial activity in the former Soviet Union. Late 20th century increases in Greenland BC may be linked to coal combustion in the rapidly expanding economies of Asia.

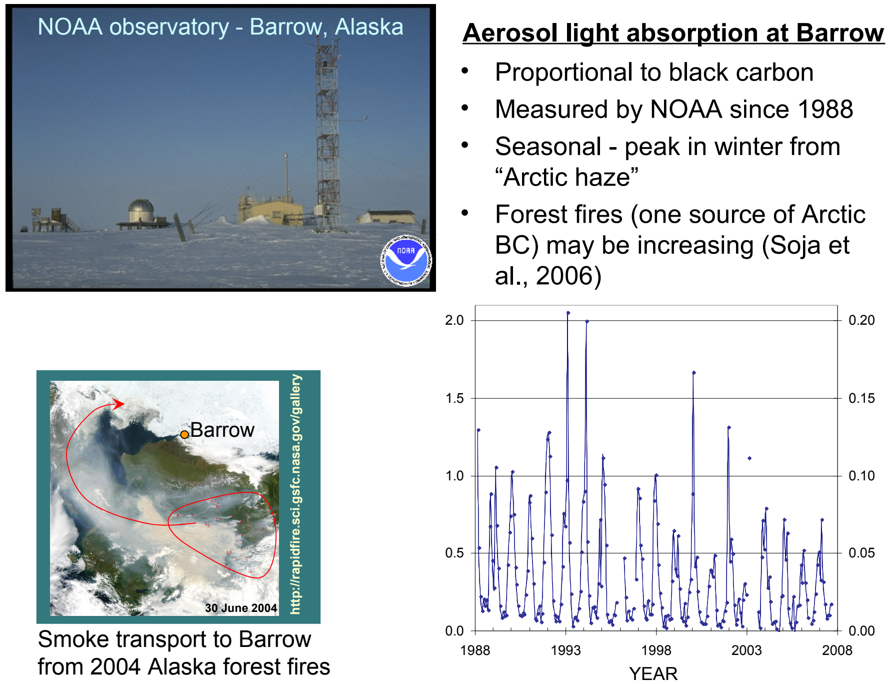

Figure 1: Light absorption, a proxy for BC, in Barrow, Alaska, 1988–2007. (J. Ogren, NOAA)

Climate Effects

In snow and ice-covered regions, BC plays an important climatic role both in the atmosphere and at the surface, i.e., before and after it is deposited. The contrast between the color of an aerosol and the planetary surface beneath it determine the net energetic effect, heating or cooling, that the aerosol has on the climate system. Black carbon is the darkest aerosol and snow and ice are, by far, the brightest surfaces of the planet. This high contrast combination causes BC to absorb sunlight and to warm the Arctic atmosphere. The direct absorption of sunlight by BC heats the Arctic atmosphere by approximately the same amount as human-injected CO_2 in spring and summer, when snow and ice are most vulnerable to melting (*Quinn et al.*, 2007). The bright aerosols (sulfate, organic matter) that are emitted from combustion along with BC have relatively little, if any, cooling effect on the Arctic because of their low contrast with the bright Arctic surface.

Black carbon also warms the Arctic, including in winter, by thickening low-level clouds that then trap more of Earth's emitted heat. BC is an important component of the Arctic Haze that peaks every winter (Figure 1). This haze increases the average cloud droplet concentration and inhibits the formation of large ice crystals which normally dessicate the cloud. The pollution-thickened clouds are more effective at trapping heat in the lower Arctic atmosphere (*Garrett and Zhao*, 2006).

Finally, BC warms the Arctic after it lands on the surface. Surface BC is an impurity that darkens the otherwise bright Arctic snow and ice, causing them to absorb more sunlight. I refer to this as "dirty snow". Dirty snow warms the Arctic surface very efficiently because the heat is trapped by the strong Arctic temperature inversions and by the insulating properties of the snow itself. Over the course of the Arctic spring, BC-contaminated snow absorbs enough extra sunlight to melt earlier—weeks earlier in some places—than clean snow.

The Intergovernmental Panel on Climate Change (IPCC) traditionally decomposes the complex

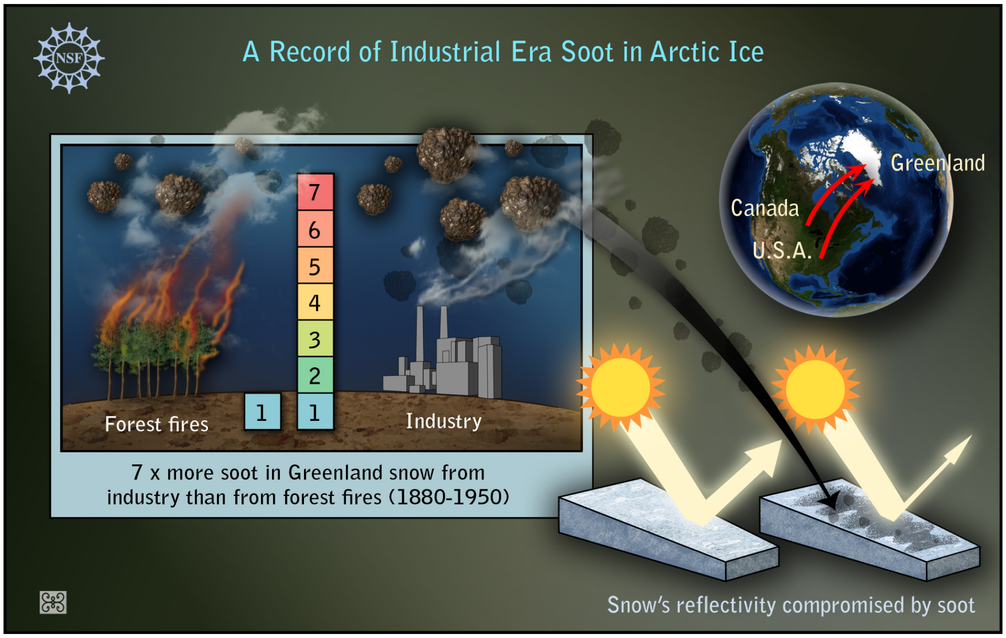

Figure 2: Industrial sources contributed seven times more BC to the Arctic than open fires from 1880–1950. (*McConnell et al.*, 2007)

effects of man-made activities on climate as a series of "radiative forcings" (Figure 3). The level of scientific understanding of aerosol-climate forcings (including Arctic BC effects) is low though steadily improving. The 2007 IPCC report explicitly recognizes for the first time the role of dirty snow and ice (i.e., surface deposition of BC) in climate change. The IPCC estimates that human-injected CO_2 traps about seventeen times more heat on Earth than dirty snow (*IPCC*, 2007).

Although highly useful for scientists and policymakers alike, such radiative forcing comparisons mis-lead when they are interpreted as the fraction of climate change caused by a given agent. One reason is that forcings applied to particularly sensitive pressure points, such as the Arctic, cause the Earth to warm more than equal forcings applied to less sensitive regions. For our purposes it is more logical to compare the *effects* of BC and CO_2 (as an established "yardstick") on temperature rather than to compare their radiative forcings (*Hansen et al.*, 2005b).

When snow, glacier, and sea-ice surfaces melt and retreat, they reveal the darker underlying surfaces such as tundra and ocean. These dark surfaces absorb even more sunlight, triggering a powerful climate-warming mechanism known as "ice-albedo feedback". BC on snow warms the planet about three times more than an equal forcing of CO_2 (*Flanner et al.*, 2007). Moreover, the BC-induced warming is concentrated in the Arctic whereas CO_2-induced warming is dispersed globally. BC appears to warm the Arctic more than any other agent except CO_2 because of its combined heating of the Arctic atmosphere and of the surface (*Jacobson*, 2004; *Flanner et al.*, 2007; *Quinn et al.*, 2007).

Until the 20th century BC was little more effective than other climate forcing agents at triggering ice-albedo warming But man-made GHGs have not only warmed the Arctic, they have exacerbated its vulnerability to warming by other pollutants such as black carbon. In the pre-industrial climate, dirty snow warmed the Arctic only by about 0.25 °C (Figure 4, *Zender and Flanner*, *Manuscript in Preparation*, hereafter ZF08). Natural soil dust (wind-blown dirt from arid regions) was then much more important at darkening the Arctic than black carbon.

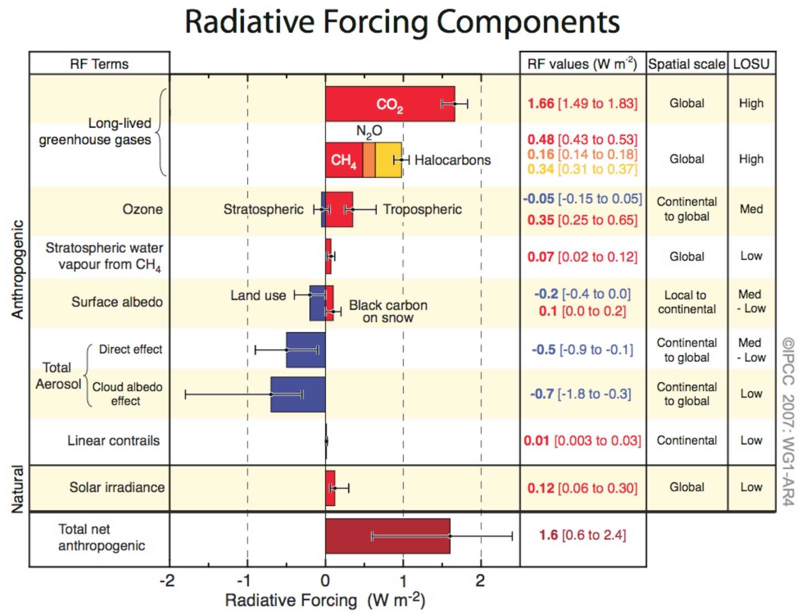

Figure 3: Global-mean radiative forcing estimates, scale, and certainty in 2005 (*IPCC*, 2007). Inter-comparing forcings can be mis-leading: BC on snow warms the planet about three times more than an equal forcing of CO_2. Moreover, the BC-induced warming is concentrated in the Arctic whereas CO_2-induced warming is dispersed globally.

Black carbon deposition from fuel combustion has warmed the Arctic by about 0.5 °C since the pre-industrial era (*Flanner et al.*, 2007) (Figure 4). Warming by dirty snow and ice occurs primarily in the frozen regions of the northern hemisphere (including the Arctic) rather than the Antarctic, which is colder and less contaminated by black carbon. In today's warmer snows, very small concentrations of BC impurities (∼10 ppb) are triggering astonishingly large ice-albedo warming.

Opportunities

The cooling power of a cleaner Arctic surface diminishes as the Arctic warms since warm snow is darker than cold snow. Snow and ice retreat also weaken black carbon's leverage over Arctic climate. Even with dramatic near-term intervention, future Arctic snow and ice cover will differ significantly from today's because of the current warming "commitment" of about 0.6 °C (*Hansen et al.*, 2005a). The spring and summer Arctic snow and sea-ice crucial for regulating Earth's temperature will be less extensive, warmer, darker, and, if current BC emission trends continue, dirtier (*Hall and Qu*, 2006). This reduced contrast between black carbon aerosol and the Arctic surface will reduce BC forcing and warming of the Arctic by mid-century (Figure 4, ZF08). Hence reducing the concentration of Arctic BC now will cool the planet more than a delayed reduction.

Nothing in climate is more aptly described as a "tipping point" than the 0 °C boundary that separates frozen from liquid water—the bright, reflective snow and ice from the dark, heat-absorbing ocean. Arctic snow, glaciers, and sea-ice are on average about 1.5 °C warmer than in the pre-industrial era. This may not sound like much, but each above-freezing day causes more melt which amplifies the strong Arctic warming effects. GHG and BC-induced warming inexorably push more of the Arctic, earlier in the year, towards its 0 °C tipping point.

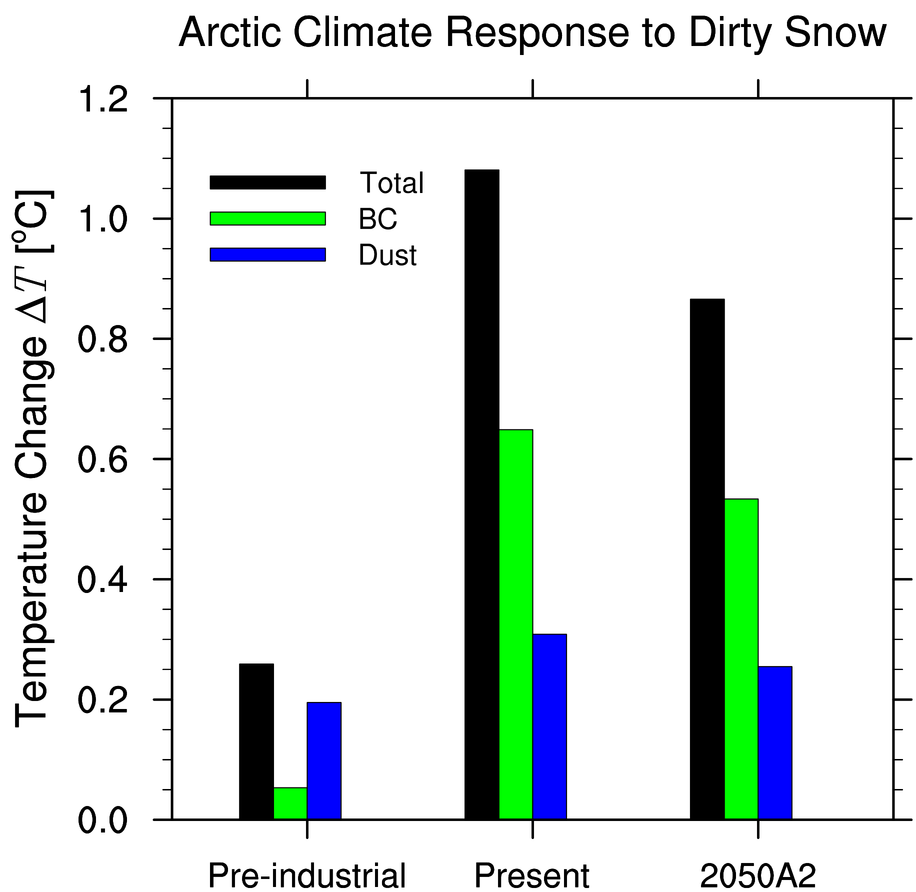

Figure 4: Predicted Arctic-mean temperature response [°C] to snowpack heating by black carbon and dust during Pre-Industrial, Present Day, and 2050 IPCC A2 climates. (*Zender and Flanner*, Manuscript in Preparation)

Man-made BC appears to have warmed the Arctic more than any other single agent besides CO_2. The most effective Arctic climate mitigation strategy would therefore target Northern Hemisphere sources of high absorptivity and low reflectance BC (e.g., diesel combustion and residential stoves) (*Quinn et al.*, 2007). Snow and ice are most vulnerable to BC emissions and deposition in spring so shifting prescribed agricultural and forest-management burns to other seasons may help to clean and brighten the Arctic. Reducing intra-Arctic BC emissions from generators and marine vessels will become increasingly important as industry and transport seek new opportunities in the thawing Arctic.

Summary

Arctic snow and ice now exist under a blanket of man-made GHGs that keeps them warmer and more vulnerable to pollution-induced melting. Arctic climate is very sensitive to the surface warming that BC causes. Aerosol heating, cloud thickening, and dirty snow explain why black carbon warms the Arctic more than any agent except CO_2. Reducing Arctic BC concentrations sooner rather than later is the most efficient way to mitigate Arctic warming that we know of.

Acknowledgments

I am grateful to M. Flanner, J. McConnell, J. Ogren, J. Randerson, P. Rasch, and S. Warren for helpful discussions and suggestions, and to F. Dominé for hosting my sabbatical at LGGE. Members of the Short-lived Pollutants and Arctic Climate (SPAC) working group synthesized many of the concepts presented here. Supported by NSF ARC-0714088 and NASA NNX07AR23G.

Download this manuscript from http://dust.ess.uci.edu/ppr/ppr_hogrc_wrt.pdf.

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