Reducing Black Carbon May Be Fastest Strategy for Slowing Climate Change

IGSD/INECE Climate Briefing Note: 9 June 2008*

Summary

Emissions of black carbon (BC) are the second largest contributor to global warming after carbon dioxide (CO_2) emissions, and reducing these emissions may be the fastest strategy for slowing climate change in the near-term, buying policymakers time to address CO_2 emissions in the middle and long-term. Estimates of BC's climate forcing (combining both direct and indirect forcings) vary from the IPCC's conservative estimate of + 0.3 watts per square meter (W/m^2) $\pm$ 0.25, to the most recent estimate of 1.0-1.2 W/m^2 (see Table 1), which is "as much as 55% of the CO_2 forcing and is larger than the forcing due to the other greenhouse gasses (GHGs) such as CH_4, CFCs, N_2O, or tropospheric ozone."[1]

In some regions, such as the Himalayas, the impact of BC on melting snowpack and glaciers may be equal to that of CO_2.[2] BC emissions also significantly contribute to Arctic ice-melt, and reducing such emissions may be "the most efficient way to mitigate Arctic warming that we know of."[3]

Since 1950, many countries have significantly reduced BC emissions, primarily to improve public health, and "technology exists for a drastic reduction of fossil fuel related BC" throughout the world.[4] Ensuring compliance and enforcement with existing national laws that address black carbon emissions can provide immediate and significant climate mitigation. New laws and regulations also are needed for further and faster reductions.

Reducing Black Carbon May Be Fastest Way to Slow Global Warming

In its the latest report, the IPCC estimated for the first time the direct radiative forcing of black carbon from fossil fuel emissions at + 0.2 W/m^2, and the radiative forcing of black carbon through its effect on the surface albedo of snow and ice at an additional + 0.1 W/m^2.[5] More recent studies and public testimony by the same scientists cited in the IPCC's report estimate that emissions from black carbon are the second largest contributor to global warming after carbon dioxide emissions, and that reducing these emissions may be the fastest strategy for slowing climate change.[6]

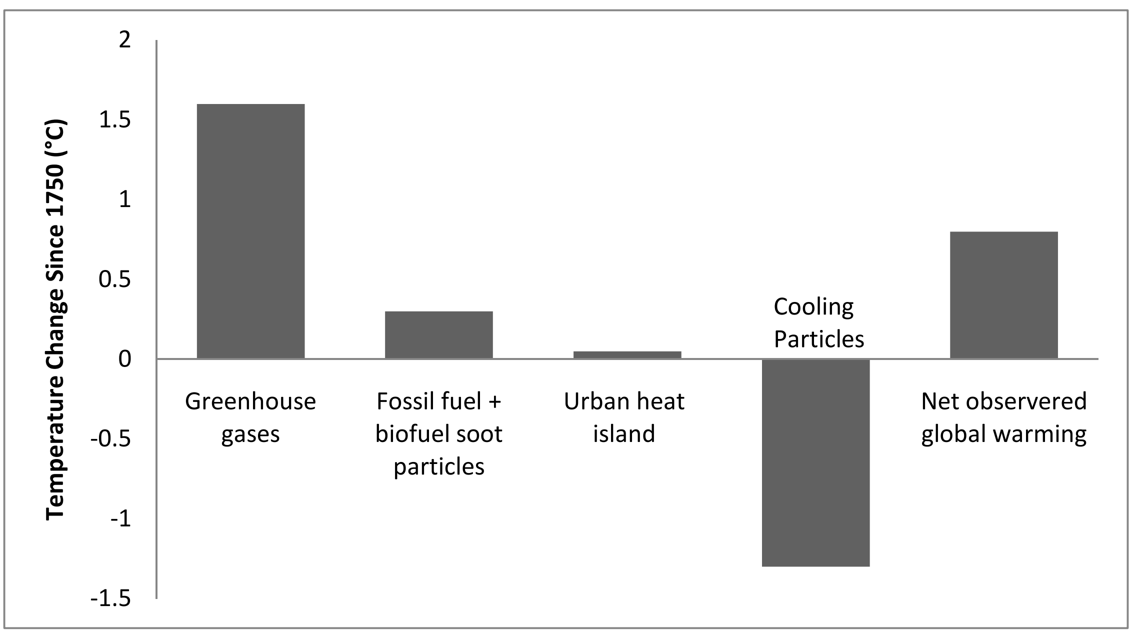
BC is formed through the incomplete combustion of fossil fuels, biofuel, and biomass, and is emitted in both anthropogenic and naturally occurring soot. BC warms the planet by absorbing heat in the atmosphere and by reducing albedo, the ability to reflect sunlight, when deposited on snow and ice. BC stays in the atmosphere from several days to weeks, whereas CO_2 has an atmospheric lifetime of more than 100 years.[7]

Given BC's relatively short lifespan, reducing BC emissions would reduce warming within weeks. Control of BC, "particularly from fossil-fuel sources, is very likely to be the fastest method of slowing global warming" in the immediate future, according to Dr. Mark Jacobson of Stanford University, and major cuts in BC emissions could slow the effects of climate change for a decade or two,[8] buying policymakers more time to reduce CO_2 emissions.[9] Reducing BC emissions could help keep the climate system from passing the tipping points for abrupt climate changes, including significant sea-level rise from the disintegration of the Greenland and/or Antarctic ice sheets.[10]

"[E]missions of black carbon are the second strongest contribution to current global warming, after carbon dioxide emissions," according to Dr. V. Ramanathan and Dr. G. Carmichael.[11] They calculate BC's combined climate forcing at 1.0 – 1.2 W/m^2, which "is as much as 55% of the CO_2 forcing and is larger than the forcing due to the other [GHGs] such as CH_4, CFCs, N_2O or tropospheric ozone."[12] Other scientists estimate the total magnitude of BC's forcing between + 0.2 to 1.1 W/m with varying ranges due to uncertainties.[2] (See Table 1.) This compares with the IPCC's climate forcing estimates of 1.66 W/m^2 for CO_2 and 0.48 W/m^2 for CH_4.[13] (See Table 2.) In addition, BC forcing is twice as effective in raising temperatures in the Northern Hemisphere and the Arctic than equivalent forcing values of CO_2.[14]

Jacobson calculates that reducing fossil fuel and biofuel soot particles would eliminate about 40% of the net observed global warming.[15] (See Figure 1.) In addition to BC, fossil fuel and biofuel soot contain aerosols and particulate matter that cool the planet by reflecting the sun's radiation away from the Earth.[16] When the aerosols and particulate matter are accounted for, fossil fuel and biofuel soot are increasing temperatures by about 0.35°C.[17]

Figure 1[18]



Primary contributions to observed global warming 1750 from the present from global model calculations. The fossil-fuel plus biofuel soot estimate takes into account the effect of soot on snow and ice albedo as well as cooling particles and particulate matter emitted with BC.

BC alone has a 20-year Global Warming Potential (GWP) of 4,470, and a 100-year GWP of 1,055-2,240.[19] Fossil fuel soot, as a result of mixing with cooling aerosols and particulate matter, has a lower 20-year GWP of 2,530, and a 100-year GWP of 840-1,280.[20]

BC Is Accelerating Warming of Arctic Sea-Ice and Himalayan Glaciers

According to the IPCC, "the presence of BC over highly reflective surfaces, such as snow and ice, or clouds, may cause a significant positive radioactive forcing."[21] The IPCC also notes that emissions from biomass burning, which usually have a negative forcing,[22] have a positive forcing over snow fields in areas such as the Himalayas.[23]

BC is a significant contributor to Arctic ice-melt, and reducing such emissions may be "the most efficient way to mitigate Arctic warming that we know of," according to Dr. Charles Zender of the University of California, Irvine.[24] The "climate forcing due to snow/ice albedo change is of the order of 1.0 W/m^2 at middle- and high-latitude land areas in the Northern Hemisphere and over the Arctic Ocean."[25] The "soot effect on snow albedo may be responsible for a quarter of observed global warming."[26] "Soot deposition increases surface melt on ice masses, and the meltwater spurs multiple radiative and dynamical feedback processes that accelerate ice disintegration," according to NASA scientists Dr. James Hansen and Dr. Larissa Nazarenko.[27] As a result of this feedback process, "BC on snow warms the planet about three times more than an equal forcing of CO_2."[28] When BC concentrations in the Arctic increase during the winter and spring due to Arctic Haze, surface temperatures increase by 0.5°C.[29]

BC emissions from northern Eurasia, North America, and Asia have the greatest impact on Arctic warming.[30] However, BC Emissions occurring within the Arctic have a proportionally larger impact on Arctic warming than emissions originating elsewhere.[31] As Arctic ice melts and shipping activity increases, emissions originating within the Arctic are expected to rise.[32]

In some regions, such as the Himalayas, the impact of BC on melting snowpack and glaciers may be equal to that of CO_2.[33] Warmer air resulting from the presence of BC in South and East Asia over the Himalayas contributes to a warming of approximately 0.6°C. [34] An "analysis of temperature trends on the Tibetan side of the Himalayas reveals warming in excess of 1°C since the 1950s."[35] This large warming trend is the proposed causal factor for the accelerating retreat of Himalayan glaciers,[36] which threatens fresh water supplies and food security in China and India.[37]

Major Producers of BC

By Region: Developed countries were once the primary source of BC emissions, but this began to change in the 1950's with the adoption of pollution control technologies in those countries.[38] Whereas the U.S. emits about 21% of the world's CO_2, it emits 6.1% of the world's soot.[39] The Unites States and the European Union could further reduce their BC emissions by accelerating implementation of BC regulations that currently take effect in 2015 or 2020[40] and by supporting the adoption of pending International Maritime Organization (IMO) regulations.[41] Existing regulations also could be expanded to increase the use of clean diesel and clean coal technologies and to develop second-generation technologies.

Today, the majority of BC emissions are from developing countries[42] and this trend is expected to increase.[43] The largest sources of BC are Asia, Latin America, and Africa.[44] China and India account for 25-35% of global BC emissions.[45] BC emissions from China doubled from 2000 to 2006.[46] Existing and well-tested technologies used by developed countries, such as clean diesel and clean coal, could be transferred to developing countries to reduce their emissions.[47]

BC emissions "peak close to major source regions and give rise to regional hotspots of BC—induced atmospheric solar heating."[48] Such hotspots include, "the Indo-Gangetic plains in South Asia; eastern China; most of Southeast Asia including Indonesia; regions of Africa between sub-Sahara and South Africa; Mexico and Central America; and most of Brazil and Peru in South America."[49] Approximately three billion people live in these hotspots.[50]

By Source: Approximately 20% of BC is emitted from burning biofuels, 40% from fossil fuels, and 40% from open biomass burning, according to Ramanathan.[51] Similarly, Dr. Tami Bond of the University of Illinois, Urbana Champaign, estimates the sources of BC emissions as follows:[52]

42%	Open biomass burning (forest and savanna burning)
18%	Residential biofuel burned with traditional technologies
14%	Diesel engines for transportation
10%	Diesel engines for industrial use
10%	Industrial processes and power generation, usually from smaller boilers
6.0%	Residential coal burned with traditional technologies[53]

BC sources vary by region. For example, the majority of soot emissions in South Asia are due to biofuel cooking, whereas in East Asia, coal combustion for residential and industrial uses plays a larger role.

Fossil fuel and biofuel soot have significantly greater amounts of BC than climate-cooling aerosols and particulate matter, making reductions of these sources particularly powerful mitigation strategies. For example, emissions from the diesel engines and marine vessels contain higher levels of BC compared to other sources.[54] Regulating BC emissions from diesel engines and marine vessels therefore presents a significant opportunity to reduce BC's global warming impact.

Biomass burning emits greater amounts of climate-cooling aerosols and particulate matter than BC, resulting in short-term cooling.[55] However, over the long-term, biomass burning may cause a net warming when CO_2 emissions and deforestation are considered.[56] Reducing biomass emissions would therefore reduce global warming in the long-term and provide co-benefits of reduced air pollution, CO_2 emissions, and deforestation. Johannes Lehmann of Cornell University estimates that by switching to slash-and-char from slash-and-burn agriculture, which turns biomass into ash using open fires that release BC[57] and GHGs,[58] 12% of anthropogenic carbon emissions caused by land use change could be reduced annually,[59] which is approximately 0.66 Gt CO_2-eq. per year, or 2% of all annual global CO_2-eq emissions.[60]

Technology for Reducing BC Is Available

Ramanathan notes that "developed nations have reduced their BC emissions from fossil fuel sources by a factor of 5 or more since 1950. Thus, the technology exists for a drastic reduction of fossil fuel related BC."[61]

Jacobson believes that "[g]iven proper conditions and incentives, [soot] polluting technologies can be quickly phased out. In some small-scale applications (such as domestic cooking in developing countries), health and convenience will drive such a transition when affordable, reliable alternatives are available. For other sources, such as vehicles or coal boilers, regulatory approaches may be required to nudge either the transition to existing technology or the development of new technology."[62]

Hansen states that "technology is within reach that could greatly reduce soot, restoring snow albedo to near pristine values, while having multiple other benefits for climate, human health, agricultural productivity, and environmental aesthetics. Already soot emissions from coal are decreasing in many regions with transition from small users to power plants with scrubbers."[63]

Jacobson suggests converting "[U.S.] vehicles from fossil fuel to electric, plug-in-hybrid, or hydrogen fuel cell vehicles, where the electricity or hydrogen is produced by a renewable energy source, such as wind, solar, geothermal, hydroelectric, wave, or tidal power. Such a conversion would eliminate 160 Gg/yr (24%) of U.S. (or 1.5% of world) fossil-fuel soot and about 26% of U.S. (or 5.5% of world) carbon dioxide."[64] According to Jacobson's estimates, this proposal would reduce soot and CO_2 emissions by 1.63 $GtCO_2$–eq. per year.[65] He notes, however, "that the elimination of hydrocarbons and nitrogen oxides would also eliminate some cooling particles, reducing the net benefit by at most, half, but improving human health," a substantial reduction for one policy in one country.[66]

Ramanathan estimates that "providing alternative energy-efficient and smoke-free cookers and introducing transferring technology for reducing soot emissions from coal combustion in small industries could have major impacts on the radiative forcing due to soot."[67] Specifically, the impact of replacing biofuel cooking with BC-free cookers (solar, bio, and natural gas) in South and East Asia is dramatic: over South Asia, a 70 to 80% reduction in BC heating; and in East Asia, a 20 to 40% reduction."[68]

Reduced BC Provides Strong Co-Benefits for Public Health and Food Security

Reducing BC emissions provides strong co-benefits for public health, with the potential to save up to three million lives a year that otherwise would be lost to air pollution (both indoor and outdoor).[69] It also provides significant co-benefits to agriculture, by reducing BC's damaging impact on plants, thereby improving crop productivity.[70]

Improving Compliance and Enforcement with Existing Laws Will Reduce Black Carbon

Many countries have existing national laws and measures regulating BC emissions, including, for example:

- laws banning or regulating slash-and-burn clearing of forests and savannahs;
- laws requiring shore-based power/electrification of ships at port, regulating idling at terminals, and mandating fuel standards for ships seeking to dock at port;
- laws requiring regular vehicle emissions tests, retirement, or retrofitting (e.g. adding particulate traps), including penalties for failing to meet air quality emissions standards, and heightened penalties for on-the-road "super-emitting" vehicles;
- laws banning or regulating the sale of certain fuels and/or requiring the use of cleaner fuels for certain uses;
- laws limiting the use of chimneys and other forms of biomass burning in urban and non-urban areas;
- laws requiring permits to operate industrial, power generating, and oil refining facilities and periodic permit renewal and/or modification of equipment; and
- laws requiring installation of scrubbers and other filtering technology for existing power generation plants, and regulating annual emissions from power generation plants.

Enforcement of these and related existing domestic measures, along with appropriate compliance assistance, will promote near-term climate mitigation, as well as strong co-benefits. Stronger laws also are needed.

Table 1: Estimates of Black Carbon Climate (Radiative) Forcings by Effect

Source	**Black Carbon Radiative Forcing (W/m^2)**				
	Direct Forcing	**Semi-Direct Effect**[71]	**Dirty Clouds Effect**[72]	**Snow/Ice Albedo Effect**	**Total**
IPCC (2007)[73]	0.2 $\pm$ 0.15	-	-	0.1 $\pm$ 0.1	0.3 $\pm$ 0.25
Jacobson (2001, 2004, and 2006)	0.55[74]	-	0.03[75]	0.06[76]	0.64[77]
Hansen (2001, 2002, 2003, 2005, and 2007)	0.2 - 0.6[78]	0.3 $\pm$ 0.3[79]	0.1 $\pm$ 0.05[80]	0.2 $\pm$ 0.1[81]	0.8 $\pm$ 0.4 (2001) 1.0 $\pm$ 0.5 (2002) ≈0.7 $\pm$ 0.2 (2003) 0.8 (2005)[82]
Hansen & Nazarenko (2004)[83]	-	-	-	~ 0.3 globally 1.0[84] arctic	-
Ramanathan (2007)[85]	0.9	-	-	0.1 to 0.3	1.0 to 1.2

Table 2: Estimated Climate Forcings (W/m2)

Component	IPCC (2007)[86]	Hansen, *et al.* (2005)[87]
CO_2	1.66	1.50
BC	.05-0.55	0.8
CH_4	0.48	0.55
Tropospheric Ozone	0.35	0.40
Halocarbons	0.34	0.30
N_2O	0.16	0.15

Endnotes

[*] Institute for Governance & Sustainable Development, http://www.igsd.org; International Network for Environmental Compliance and Enforcement, http://www.inece.org.

[1] V. Ramanathan and G. Carmichael, *Global and regional climate changes due to black carbon*, 1 NATURE GEOSCIENCE 221-22 (23 March 2008) ("The BC forcing of 0.9 W m–2 (with a range of 0.4 to 1.2 W m–2) … is as much as 55% of the CO_2 forcing and is larger than the forcing due to the other GHGs such as CH_4, CFCs, N_2O or tropospheric ozone.")

[2] *Id*. at 221 and 224.

[3] Charles Zender, Written Testimony for the Hearing on Black Carbon and Climate Change, U.S. House Committee on Oversight and Government Reform 6 (18 October 2007), *available at* http://oversight.house.gov/documents/20071018110919.pdf [hereinafter Zender Testimony] ("Reducing Arctic BC concentrations sooner rather than later is the most efficient way to mitigate Arctic warming that we know of.").

[4] V. Ramanathan, Testimony for the Hearing on Black Carbon and Climate Change, U.S. House Committee on Oversight and Government Reform 4 (18 October 2007), *available at* http://oversight.house.gov/story.asp?ID=1550 [hereinafter Ramanathan Testimony].

[5] IPCC, *Changes in Atmospheric Constituents and in Radiative Forcing*, in CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 129, 136, 163 (2007), *available at* http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

[6] *See id*. at 164, 170, 174-76, 217-34 (citing studies by Ramanathan, Jacobson, Zender, Hansen, and Bond); *supra* notes 3-4 (Zender Testimony and Ramanathan Testimony); *infra* notes 9 and 42 (Jacobson Testimony and Bond Testimony).

[7] V. Ramanathan & G. Carmichael, *supra* note 1, at 226.

[8] Ramanathan Testimony, *supra* note 4, at 3 ("Thus a drastic reduction in BC has the potential of offsetting the CO_2 induced warming for a decade or two.").

[9] Mark Z. Jacobson, Testimony for the Hearing on Black Carbon and Climate Change, U.S. House Committee on Oversight and Government Reform 12 (18 October 2007), *available at* http://oversight.house.gov/documents/20071018110606.pdf [hereinafter Jacobson Testimony]; V. Ramanathan and G. Carmichael, *supra* note 1, at 226 (Reducing future black carbon, or soot, emissions "offers an opportunity to mitigate the effects of global warming trends in the short term," according to Dr. V. Ramanathan of the Scripps Institution of Oceanography and Dr. G. Carmichael of the University of Iowa. Drastic climate mitigation results from BC's "significant contribution to global radiative forcing" and its "much shorter lifetime [estimated to be one week] compared with CO_2 [which has a lifetime of 100 years or more]").

[10] Timothy Lenton, Hermann Held, Elmar Kriegler, Jim Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber, *Tipping elements in the Earth's climate system*, 105 PROC. OF THE NAT'L ACAD. OF SCI. 6 (12 February 2008)

("The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet. . ."); J. Hansen, *Climate Catastrophe*, NEW SCIENTIST (28 July 2007) (...the primary issue is whether global warming will reach a level such that ice sheets begin to disintegrate in a rapid, non-linear fashion on West Antarctica, Greenland or both.").
[11] V. Ramanathan and G. Carmichael, *supra* note 1, at 221 (". . . emissions of black carbon are the second strongest contribution to current global warming, after carbon dioxide emissions.") Numerous scientists also calculate that BC may be second only to CO_2 in its contribution to climate change, including Tami C. Bond & Haolin Sun, *Can Reducing Black Carbon Emissions Counteract Global Warming*, ENVIRON. SCI. TECHN. (2005), at 5921 ("BC is the second or third largest individual warming agent, following carbon dioxide and methane."); *and* J. Hansen, *A Brighter Future*, 53 CLIMATE CHANGE 435 (2002), *available at* http://pubs.giss.nasa.gov/docs/2002/2002_Hansen_1.pdf (calculating the climate forcing of BC at 1.0 +/- 0.5 W/m^2).
[12] V. Ramanathan and G. Carmichael, *supra* note 1, at 222.
[13] IPCC, *Technical Summary*, in CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 21 (2007) *available at* http://www.ipcc.ch/ipccreports/ar4-wg1.htm.
[14] James Hansen & Larissa Nazarenko, *Soot Climate Forcing Via Snow and Ice Albedos*, 101 PROC. OF THE NAT'L ACAD. OF SCI. 423 (13 January 2004) ("The efficacy of this forcing is ≈2 (i.e. for a given forcing it is twice as effective as CO2 in altering global surface air temperature)").
[15] Gross global warming should result in about 2°C temperature rise. However, observed global warming is only about .8°C because cooling particles off set much of the warming. Reducing fossil fuel and biofuel soot would reduce about 40% of the observed warming and about 16% of the gross warming. Jacobson Testimony, *supra* note 9, at 3. ("The figure also shows that fossil-fuel plus biofuel soot may contribute to about 16% of gross global warming (warming due to all greenhouse gases plus soot plus the heat island effect), but its control in isolation could reduce 40% of net global warming.").
[16] Jacobson Testimony, *supra* note 9, at 4.
[17] Jacobson Testimony, *id.*
[18] Jacobson Testimony, *id. at* 3.
[19] Jacobson Testimony, *id.*
[20] Jacobson Testimony, *id.*
[21] IPCC, *supra* note 13, at 397. ("While the radiative forcing is generally negative, positive forcing occurs in areas with a very high surface reflectance such as desert regions in North Africa, and the snow fields of the Himalayas."); J. Hansen & L. Nazarenko, *supra* note 14, at 425. (The brown haze over India, heavy with fossil fuel and biofuel soot, reaches to the Himalayas. If prevailing winds deposit even a fraction of this soot on glaciers, the snow BC content could be comparable to that in the Alps.").
[22] J. Hansen, *et al*., *Efficacy of Climate Forcing*, 110 J. GEOPHYS. RES. D18104, 1 (2005), *available at* http://pubs.giss.nasa.gov/docs/2005/2005_Hansen_etal_2.pdf (Accounting for forcing efficacies and for indirect effects via snow albedo and cloud changes, we find that fossil fuel soot, defined as BC + OC (organic carbon), has a net positive forcing while biomass burning BC + OC has a negative forcing).
[23] IPCC, *supra* note 13, at 397.
[24] Zender Testimony, *supra* note 3, at 6.
[25] J. Hansen & L. Nazarenko, *supra* note 14, at 425.
[26] J. Hansen & L. Nazarenko, *id*. at 428.
[27] J. Hansen & L. Nazarenko, *id*. at 425.
[28] Zender Testimony, *supra* note 3, at 4 (figure 3); *See* J. Hansen & L. Nazarenko, *supra* note 14, at 426. ("The efficacy for changes of Arctic sea ice albedo is >3. In additional runs not shown here, we found that the efficacy of albedo changes in Antarctica is also >3."); *See also* Flanner, M.G., C.S. Zender, J.T. Randerson, and P.J. Rasch, *Present-day climate forcing and response from black carbon in snow*, 112 J. GEOPHYS. RES. D11202 (2007) ("The forcing is maximum coincidentally with snowmelt onset, triggering strong snow-albedo feedback in local springtime. Consequently, the "efficacy" of BC/snow forcing is more than three times greater than forcing by CO_2.").
[29] P.K. Quinn, T.S. Bates, E. Baum, N. Doubleday, A.M. Fiore, M. Flanner, A. Fridlind, T.J. Garrett, D. Koch, S. Menon, D. Shindell, A. Stohl, and S.G. Warren. *Short-lived Pollutants in the Arctic: Their Climate Impact and Possible Mitigation Strategies*, 8 ATMOS. CHEM. PHYS. 1723, 1731 (2008); *See* David Shukman, *Vast Cracks Appear in Arctic Ice*, BBC NEWS (23 May 2008), *available at* http://news.bbc.co.uk/2/hi/science/nature/7417123.stm (A recent expedition study by Canada confirmed vast cracks stretching for more than 10 miles on Ward Hunt).
[30] P.K. Quinn, *supra* note 29, at 1732.
[31] P.K. Quinn, *id*.
[32] P.K. Quinn, *id*. at 1732; J. Hansen & M. Sato, *et al.*, *Dangerous Human-Made Interference with Climate: a GISS modelE Study* 7 ATMOS. CHEM. PHYS. DISCUSS. 2287, 2298, 2296 (2007)("We suggest that Arctic climate change has been driven

as much by pollutants (0_3, its precursors CH_4 and soot) as by CO2 . . . .Thus, in that case, reduction of some of the pollutants [including soot] may make it possible to keep further Arctic warming very small and thus probably avoid loss of all sea ice.”).

[33] V. Ramanathan & G. Carmichael, *supra* note 1, at 221.

[34] V. Ramanathan & G. Carmichael, *supra* note 1, at 224.

[35] V. Ramanathan & G. Carmichael, *supra* note 1, at 224.

[36] V. Ramanathan & G. Carmichael, *supra* note 1, at 224.

[37] Lester R. Brown, *Melting Mountain Glaciers Will Shrink Grain Harvests in China and India*, PLAN B UPDATE, Earth Policy Institute (20 March 2008), *available at* http://www.earth-policy.org/Updates/2008/Update71.htm (Melting Himalayan glaciers will soon reduce water supply for major Chinese and Indian rivers (Ganges, Yellow River, Yangtze River) that irrigate rice and wheat crops that feed hundreds of millions and “could lead to politically unmanageable food shortages.”).

[38] V. Ramanathan & G. Carmichael, *supra* note 1, at 221 (“Until about the 1950s, North America and Western Europe were the major sources of soot emissions, but now developing nations in the tropics and East Asia are the major source problem.”).

[39] Jacobson Testimony, *supra* note 9, at 4.

[40] Clean Air Fine Particle Implementation Rule, 72 Fed. Reg. 20586, 20587 (April 25, 2007) (to be codified as 40 C.F.R. pt. 51), *available at* http://www.epa.gov/fedrgstr/EPA-AIR/2007/April/Day-25/a6347.pdf; Press Release, European Union, Environment: Commission welcomes final adoption of the air quality directive, (April 14, 2008), *available at* http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/570&format=HTML&aged=0&language=EN&guiLanguage=en.

[41] International Maritime Organization, Press Release, IMO Environment meeting Approves Revised Regulations on Ship Emissions, International Maritime Organization (4 April 2008), *available at* http://www.imo.org/About/mainframe.asp?topic_id=1709&doc_id=9123(The IMO has approved amendments to MARPOL Annex VI *Regulations for the Prevention of Air Pollution from Ships* which are now subject to adoption at an October 2008 meeting.).

[42] Tami Bond, Testimony for the Hearing on Black Carbon and Climate Change, U.S. House Committee on Oversight and Government Reform 2-3 (October 18, 2007), *available at* http://oversight.house.gov/documents/20071018110647.pdf [hereinafter Bond Testimony].

[43] Jacobson Testimony, *supra* note 9, at 5.

[44] Tami Bond, *Summary: Aerosols*, Air Pollution as a Climate Forcing: A Workshop, Honolulu, Hawaii, April 29-May 3, 2002, *available at* http://www.giss.nasa.gov/meetings/pollution2002.

[45] V. Ramanathan & G. Carmichael, *supra* note 1, at 226.

[46] V. Ramanathan & G. Carmichael, *supra* note 1, at 226.

[47] Ramanathan Testimony, *supra* note 4, at 4.

[48] V. Ramanathan & G. Carmichael, *supra* note 1, at 221.

[49] V. Ramanathan & G. Carmichael, *id.*

[50] V. Ramanathan & G. Carmichael, *id.*

[51] V. Ramanathan & G. Carmichael, *id.* at 224.

[52] *See* Bond Testimony, *supra* note 42, at 2 (figure 1).

[53] Bond Testimony, *id.* at 1-2.

[54] Jacobson Testimony, *supra* note 9, at 5-6 (showing that shipping emissions produce more than 3 times as much BC as POC, while off-road vehicles produce 40% more BC than POC, and on-road vehicles produce 25-60% more BC than POC).

[55] J. Hansen *et al.*, *Efficacy of Climate Forcing*, *supra* note 22.

[56] Mark. Z. Jacobson, *The Short-Term Cooling but Long-Term Global Warming Due to Biomass Burning*, 17 J. OF CLIMATE 2909, 2923 (“. . . whereas aerosol particles emitted during burning may cause a short-term cooling of global climate, longer-lived greenhouse gases may cause warming (or cancel the cooling) after several decades. As such, reducing biomass burning may cause short-term warming but long-term cooling or no change in temperature. Although the eventual cooling may not appear for many years, its magnitude may be as large as 0.6 K after 100 yr.”).

[57] Surabi Menon, James Hansen, Larissa Nazarenko, & Yunfeng Luo, *Climate Effects of Black Carbon*, 297 SCIENCE 2250, 2250 (27 September 2002) (Black Carbon emissions are “a product of incomplete combustion from coal, diesel engines, biofuels, and outdoor biomass burning . . .”).

[58] *See* Lehmann, *et al*., *Bio-Char Sequestration in Terrestrial Ecosystems – A Review*, 11 MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE 403, at 403-07, 418 (Springer 2006), *available at* http://www.css.cornell.edu/faculty/lehmann/publ/MitAdaptStratGlobChange%2011,%20403-427,%20Lehmann,%202006.pdf ; *See id.* at 407 (Researchers estimate that between 38-84% of the biomass carbon in

vegetation is released during the burn, whereas converting the biomass into bio-char by means of simple kiln techniques sequesters more than 50% of this carbon in bio-char).
[59] *Id.* at 407-08.
[60] *See* Raupach, Michael, *et al.*, *Global and Regional Drivers of Accelerating CO_2 Emissions*, 104 PROC. OF THE NAT'L ACAD. OF SCI. 24, (underlying data *available at*, http://www.pnas.org/cgi/content/full/0700609104/DC1) (indicating that between 2000-2005 land use emissions annually represented on average 1.5 GtC of the total 8.7 GtC global emissions or 5.5 Gt CO_2 eq. of 31.9 Gt CO_2 eq. of global emissions—17.25% of total. A reduction of 12% of land use emissions equals 0.66 Gt CO_2 eq., approximately 2% of annual global CO_2 eq. emissions. Lehmann's original estimates were based on a 0.2 GtC offset of the 1.7 GtC emissions from land use change estimated in 2001 by the IPCC). *See also* Lehmann, *et al., supra* note 49, at 407-08. (Given the increase in fossil fuel emissions to 8.4 GtC, total anthropogenic emissions in 2006, including the estimated 1.5 GtC from land use change, were 9.9 GtC. Thus, despite an increase in overall CO_2 eq. emissions, using Lehmann's original 0.2 GtC reduction still results in an approximate 2% reduction in global CO_2 eq. emissions). *See* Global Carbon Budget Team, *Recent Carbon Trends and the Global Carbon Budget*, the Global Carbon Project, (15 November 2007), *available at* http://www.globalcarbonproject.org/global/pdf/GCP_CarbonCycleUpdate.pdf (giving 2006 global carbon emissions estimates).
[61] Ramanathan Testimony, *supra* note 4, at 4.
[62] Jacobson Testimony, *supra* note 9*,* at 5.
[63] J. Hansen & L. Nazarenko, *supra* note 14, at 428.
[64] Jacobson Testimony, *supra* note 9*,* at 9.
[65] Jacobson offers an estimate of total U.S. CO_2 emissions in 2005 of 6270 metric tonnes, 26% of which is 1630. *Id*.
[66] Jacobson Testimony, *supra* note 9*,* at 9.
[67] V. Ramanathan & G. Carmichael, *supra* note 1, at 226.
[68] V. Ramanathan & G. Carmichael, *id.*
[69] Mark Jacobson, *Control of Fossil-Fuel Particulate Black Carbon and Organic Matter, Possibly the Most Effective Method of Slowing Global Warming,* 107 J. GEOPHYS. RES. D19 (2002) (*citing* C. A. Pope III and D. W. Dockery, *Epidemiology of particle effects*, in S. T. Holgate, *et al*., eds., AIR POLLUTION AND HEALTH 673– 705 (1999) and statistics from the World Health Organization).
[70] *See* Mike Bergin, *The Influence of Aerosols on Plant Growth*, Day 4 of Air Pollution as a Climate Forcing: A Workshop (2002), *available at* http://www.giss.nasa.gov/meetings/pollution2002/d4_bergin.html.
[71] Mark Z. Jacobson, *Effects of Anthropogenic Aerosol Particles and Their Precursor Gases on California and South Coast Climate*, California Energy Commission, 6 (Nov. 2004), *available at* http://www.stanford.edu/group/efmh/jacobson/CEC-500-2005-003.PDF (BC's semi-direct effect occurs when "solar absorption by a low cloud increases stability below the cloud, reducing vertical mixing of moisture to the could base, thinning the cloud.").
[72] *Carbon's Other Warming Role*, GEOTIMES (May 2001), *available at* http://www.geotimes.org/mar01/warming.html (BC produces "dirty cloud droplets, causing an "indirect" impact that reduces a cloud's reflective properties.").
[73] IPCC, *Changes in Atmospheric Constituents and in Radiative Forcing,* in CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS,CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 129, 163-64, and 185 (2007) (estimating the direct radiative forcing of BC at 0.2 $W/m^2 \pm 0.15$ and the indirect of effect of BC on snow and ice surface albedo at 0.1 $W/m^2 \pm 0.1$).
[74] Mark Z. Jacobson, *Strong Radiative Heating Due to the Mixing State of Black Carbon in Atmospheric Aerosols*, NATURE, 409, 695-697 (2001) ("The final yearly averaged direct forcing due to BC in the external mixture, the multiple-distribution coated-core, and the single internally-mixed, coated-core distribution cases from Fig. 3 were 0.31, 0.55 and 0.62 W m-2, respectively. The multiple-distribution BC direct forcing (0.55) falls between direct-forcing estimates for CH4 (0.47 W/m^2) and CO2 (1.56 W/m^2) from IPCC [2001].").
[75] Mark Z. Jacobson, *Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity*, 109 J. GEOPHYS. RES. D21201 (2004). (Dirty Clouds Effect of .03 W m-2)
[76] Mark Z. Jacobson, *Effects of Externally-Through-Internally-Mixed Soot Inclusions within Clouds and Precipitation on Global Climate*, 110 J. PHYS. CHEM. A. 6860-6873 (2006). (Snow/Ice Albedo Effect of .06 W m-2)
[77] This figure has been obtained by adding Jacobson's estimates for BC's direct and indirect forcings. *See supra*, notes 76-78 and accompanying text.
[78] James E. Hansen and Makiko Sato, Figure 1 in *Trends of Measures Climate Forcing Agents*, 98 PROC. OF THE NAT'L ACAD. OF SCI. 14778, 14779 (2001). (Hansen 2001 estimate – Direct Forcing – 0.6 W/m^2 Total forcing – 0.8 $\pm$ 0.4 W/m^2); J. Hansen, *supra* note 11, at 435 (Hansen 2002 estimate – "My present estimate for global climate forcings caused by BC is: (1) 0.4 $\pm$ 0.2 W/m^2 direct effect, (2) 0.3 $\pm$ 0.3 W/m^2 semi-direct effect (reduction of low level clouds due to BC heating; Hansen et al., 1997), (3) 0.1 $\pm$ 0.05 W/m^2 'dirty clouds' due to BC droplet nuclei, (4) 0.2 $\pm$ 0.1 W/m^2 snow and ice darkening due to BC deposition. … The uncertainty estimates are subjective. The net BC forcing implied is 1 + 0.5 W/m^2."); J. Hansen, *et al*., *Climate Change and Trace Gases*, 365 PHIL. TRANS. R. SOC. 1925, 1942 (2007) (Hansen 2007

estimate – "Soot from fossil fuel burning, i.e. highly absorbing aerosols that contain black carbon (BC) and organic carbon (OC), are estimated to cause a global climate forcing of 0.22 W m^{-2}. This is a conservative estimate for fossil fuel BC forcing . . . because it assumes a high OC/BC ratio for fossil fuel emissions. In addition, it assigns 50% of the aerosol indirect effect (which causes cooling) to soot (BC/OC).").

[79] J. Hansen, *supra* note 11, at 435 (Hansen 2002 estimate – "My present estimate for global climate forcings caused by BC is: (1) 0.4 ± 0.2 W/m^2 direct effect, (2) 0.3 ± 0.3 W/m^2 semi-direct effect (reduction of low level clouds due to BC heating; Hansen et al., 1997), (3) 0.1 ± 0.05 W/m^2 'dirty clouds' due to BC droplet nuclei, (4) 0.2 ± 0.1 W/m^2 snow and ice darkening due to BC deposition. … The uncertainty estimates are subjective. The net BC forcing implied is 1 + 0.5 W/m^2.").

[80] J. Hansen, *supra* note 11, at 435 (Hansen 2002 estimate – "My present estimate for global climate forcings caused by BC is: (1) 0.4 ± 0.2 W/m^2 direct effect, (2) 0.3 ± 0.3 W/m^2 semi-direct effect (reduction of low level clouds due to BC heating; Hansen et al., 1997), (3) 0.1 ± 0.05 W/m^2 'dirty clouds' due to BC droplet nuclei, (4) 0.2 ± 0.1 W/m^2 snow and ice darkening due to BC deposition. … The uncertainty estimates are subjective. The net BC forcing implied is 1 + 0.5 W/m^2.").

[81] J. Hansen, *supra* note 11, at 435 (Hansen 2002 estimate – "My present estimate for global climate forcings caused by BC is: (1) 0.4 ± 0.2 W/m^2 direct effect, (2) 0.3 ± 0.3 W/m^2 semi-direct effect (reduction of low level clouds due to BC heating; Hansen et al., 1997), (3) 0.1 ± 0.05 W/m^2 'dirty clouds' due to BC droplet nuclei, (4) 0.2 ± 0.1 W/m^2 snow and ice darkening due to BC deposition. … The uncertainty estimates are subjective. The net BC forcing implied is 1 ± 0.5 W/m^2.").

[82] James E. Hansen and Makiko Sato, Figure 1 in *Trends of Measures Climate Forcing Agents*, 98 PROC. OF THE NAT'L ACAD. OF SCI. 14778, 14779 (2001). (Hansen 2001 estimate – Direct Forcing – 0.6 W m-2, Total forcing – 0.8 + 0.4 W m-2); J. Hansen, *supra* note 11, at 435 (Hansen 2002 estimate – "My present estimate for global climate forcings caused by BC is: (1) 0.4 ± 0.2 W/m^2 direct effect, (2) 0.3 ± 0.3 W/m^2 semi-direct effect (reduction of low level clouds due to BC heating; Hansen et al., 1997), (3) 0.1 ± 0.05 W/m^2 'dirty clouds' due to BC droplet nuclei, (4) 0.2 ± 0.1 W/m^2 snow and ice darkening due to BC deposition. … The uncertainty estimates are subjective. The net BC forcing implied is 1 + 0.5 W/m^2."); Makiko Sato, James Hansen, Dorthy Koch, Andrew Lacis, Reto Ruedy, Oleg Dubovik, Brent Holben, Mian Chin, and Tica Novakov, *Global Atmospheric Black Carbon Inferred from AERONET,* 100 PROC. OF THE NAT'L ACAD. OF SCI. 6319, at 6323 (2003) (… we estimate the anthropogenic BC forcing as ≈0.7 ± 0.2 W/m^2."); J. Hansen, *et al*., *Climate Change and Trace Gases*, 365 PHIL. TRANS. R. SOC. 1925, 1942 (2007) (Hansen 2007 estimate – "Soot from fossil fuel burning, i.e. highly absorbing aerosols that contain black carbon (BC) and organic carbon (OC), are estimated to cause a global climate forcing of 0.22 W m^{-2}. This is a conservative estimate for fossil fuel BC forcing . . . because it assumes a high OC/BC ratio for fossil fuel emissions. In addition, it assigns 50% of the aerosol indirect effect (which causes cooling) to soot (BC/OC).").

[83] J. Hansen & L. Nazarenko, *supra* note 14, 426 ("the effective forcing for the assigned snow albedo change in the most realistic cases 1 and 2 is F_e ~0.6 W/m^2 in the Northern Hemisphere or F_e ~0/3 W/m^2 globally.").

[84] *Id*., at 425 (The "climate forcing due to snow/ice albedo change is of the order of 1 W/m^2 at middle- and high-latitude land areas in the Northern Hemisphere and over the Arctic Ocean.").

[85] Ramanathan Testimony, *supra* note 4.

[86] IPCC, *supra* note 3.

[87] J. Hansen, *et al*., *Efficacy of Climate Forcing*, *supra* note 22.