APPENDIX U

PROPOSED

LEV III CLIMATE CHANGE IMPACTS OF BLACK CARBON PARTICLES

TECHNICAL SUPPORT DOCUMENT

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I. INTRODUCTION

Airborne particles in the ambient air play an important role in the overall energy balance of the atmosphere by scattering and absorbing incoming and outgoing solar and terrestrial radiation (the “direct effect”) and by modifying the microphysical properties of clouds (the “indirect effects”) through their role as cloud condensation nuclei and/or ice nuclei . Direct and indirect effects on the climate by atmospheric particles remain one of the principal uncertainties in estimates of total anthropogenic radiative forcing. But recent advances in the understanding of the role of particles in the global energy balance are closing the existing knowledge gaps. Changes to the Earth’s radiation balance can impact the climate at both global and regional scales.

The chemical composition and climate change impacts of particles vary with their sources; for example, particles emitted into the air as urban industrial pollution influence the climate vary differently from windblown desert dust or sea salt particles. To further complicate this picture, particles tend to remain in the air for only a few days to about a week, resulting in extreme spatial and temporal variability over the surface of the Earth. Major components of fine particles such as sulfate, nitrate, organic compounds, dust, and sea salts have reflective properties that scatter radiation (negative radiative forcing or cooling impact). Carbonaceous particles (those that contain organic and black carbon) are particularly important because of their abundance in the atmosphere, and the characteristics of the carbon vary significantly depending on their origin. Black carbon (BC) is the principal absorber of visible solar radiation in the atmosphere while organic carbon (OC) is often described as light-reflecting compounds. Recent studies show that certain fractions of organic carbon can also absorb solar radiation efficiently but differ from typical BC, and they are referred to as “brown carbon”[1]. Its sources are known to be low-temperature biomass and biofuel burning as well as heterogeneous or multiphase processes that are not clearly determined yet. In addition, optical and chemical properties of brown carbon have not been determined consistently[2]. Further work is necessary through both observations and improved model simulation of brown carbon particle for better assessing its effects on climate.

The major anthropogenic sources of BC are fossil fuels and biofuels (biomass burning for domestic energy). The atmospheric fate and climate impacts of BC from different regions differ considerably. Atmospheric processes that occur after BC is emitted, such as mixing, aging, and coating, also affect the net influence of BC on climate. Because the climate effects of BC aerosol depend strongly on its physical and chemical properties, as well as on its residence time and distribution in the

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[1] Lukacs, H., et al., (2007). Seasonal trends and possible sources of brown carbon based on 2-year aerosol measurements at six sites in Europe. Journal of Geophysical Research e Atmospheres 112. http://publik.tuwien.ac.at/files/pub-tch_7878.pdf

[2] Yang, M.; Howell, S.G.; Zhuang, J.; Huebert, B.J. (2009). Attribution of aerosol light absorption to black carbon, brown carbon, and dust in China -interpretations of atmospheric measurements during EAST-AIRE. Atmos. Chem. Phys., 9(6): 2035-2050.http://www.atmos-chem-phys.org/9/2035/2009/acp-9-2035-2009.pdf

atmosphere[3], a thorough understanding of these properties and accurate techniques for the determination of BC in the atmosphere and from sources are deemed essential.

In principle, the relatively strong light absorption properties of BC can be used to infer BC from an optical measurement and knowledge of the mass specific absorption of BC. Estimates of BC are made with a variety of instrumentation and measurement techniques. This has also resulted in a variety of definitions related to chemical and/or physical particle properties, intended applications, and the different measurement and estimation approaches, and has given rise to an array of descriptive terms such as "graphitic carbon", "elemental carbon", "black carbon", and "soot" which are used in the literature as interchangeable with BC. Light absorption, BC, and elemental carbon derived from different measurement methods and in different environments have been compared in more than 100 reports and publications[4]. Among commonly used methods, the results are highly correlated, but the absolute values can differ by factors of two or more. Nevertheless, a high correlation among values for different methods suggests that empirical relationships might be established that would allow some predictability of one type of measurement from another.

The large interest in airborne particles and their radiative impact is derived in part from the Intergovernmental Panel on Climate Change (IPCC)'s[5] conclusion that human-caused climate change has resulted primarily from changes in the amounts of greenhouse gases (GHGs) in the atmosphere, but also from changes in small particles. In recent years there has been increased attention in the particle research community about the potential of BC to cause global warming. The ability of BC to absorb light energy and its role in key atmospheric processes link it to a range of climate impacts, including increased temperatures, accelerated ice and snow melt, and disruptions to precipitation patterns. It has been proposed that light absorbing particles in the atmosphere act as a greenhouse pollutant whose net forcing is warming and is second only to carbon dioxide (CO_2). Ramanathan and Carmichael [6] estimate a BC forcing of 0.9 watts per square meter (W/m^2) or more than half of the 1.6 W/m^2 for CO_2. This estimate of the forcing due to BC is larger than most prior estimates including those of the IPCC 4th assessment report.

Numerous national and international reports highlight the critical role of BC in climate change. EPA, in consultation with other Federal agencies, prepared a comprehensive report[7] to Congress on the climate effects of BC. The report synthesized available information on sources of BC, its impacts on global and regional climate, and the

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[3] Jacobson, M. Z., (2001) Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols *Nature, 409*, 695-697. http://www.stanford.edu/group/efmh/jacobson/Articles/VI/nature.pdf

[4] Watson, J.G., Chow, J.C., Chen, L.-W.A., (2005). Summary of Organic and Elemental Carbon/Black Carbon Analysis Methods and Inter-comparisons. AAQR 5, 65-102. http://aaqr.org/VOL5_No1_June2005/6_AAQR-05-06-OA-0006_65-102.pdf

[5] IPCC (2007), Working Group I: The Physical Science Basis, Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing, available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

6. Ramanathan, V. and Carmichael, G. (2008) Global and regional climate changes due to black carbon. Nature Geoscience 156, 221-227.

[7] EPA (2011). Report to Congress on Black Carbon External Peer Review Draft. EPA-450/D-11-001, March 2011.

potential utility and cost-effectiveness of mitigation options for reducing climate and public health impacts of BC. The United Nations Environment Program (UNEP)[8] recently released a report which summarizes findings and conclusions of an assessment of BC and tropospheric ozone. The assessment looks into all aspects of anthropogenic emissions of BC and tropospheric ozone precursors, such as methane. It examines a large number of potential measures to reduce harmful emissions, identifying a small set of specific measures that would likely produce the greatest benefits, and which could be implemented with currently available technology. In May 2011, a task force, convened by the Arctic Council, produced a comprehensive technical document [9] on assessment of emissions and mitigation options for black carbon. The task forces has compiled and compared national and global BC emissions inventories, examined emission trends and projections, synthesized existing policies and programs, and identified additional emission mitigation opportunities for BC.

The heightened interest in BC mitigation today is built on the well-recognized association of these emissions with localized air pollution and their severe negative health impacts while also achieving significant climate co-benefits. Understanding the role played by BC is therefore critical for three reasons: from the perspective of understanding climate change, distinguishing between those particles that are exacerbating the GHG impacts from those that are masking it (through their cooling effect) is important. That understanding will allow better characterization of the source impacts and identifying mitigation options. The second reason is that unlike carbon dioxide, BC's effects are immediate, lasting only a matter of weeks, and are regional in their effect. Thus, a mitigation strategy of reducing BC emissions in certain locations would create an immediate relative cooling. This means buying some time and avoiding going beyond some of the irreversible tipping points such as the melting of arctic ice and mountain snowpacks. Third, BC, as a key component of fine particulate matter (PM2.5), contributes to harmful health effects, including premature death. If BC can indeed provide a double win from both a global climate and local air pollution perspective, it makes the strong case for climate action that much more compelling.

The following is a summary of the current scientific knowledge on black carbon, including where it comes from, its atmospheric effects, the overall impact on environment, and the need for motor vehicle control.

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[8] UNEP (2011). Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers. http://www.unep.org/dewa/Portals/67/pdf/Black_Carbon.pdf

[9] Arctic Council (2011). Technical report of the Arctic Council Task Force on Short-Lived Climate Forcers. http://arctic-council.org/filearchive/ACTF_Report_22July2011.pdf).

I.

II. OVERVIEW OF RELEVANT SOURCES OF BC

To curb the warming caused by BC, two questions must be answered: where did the BC come from, and what created it. In general, sources of BC include either (a) activities or technologies that emit BC, and (b) geographic areas or regions from where BC is transported to elsewhere. Neither of these is susceptible to easy analysis, mostly because BC is an air pollutant that is regulated indirectly, if at all. For example, some nations and states regulate particulate matter, which includes BC, but other constituents as well. No nation, however, has yet adopted a requirement that directly and explicitly regulates BC, whether for the purpose of protecting human health or curbing global warming.

BC comes from both open biomass burning and from energy-related burning. In developing countries, biomass burning and residential sources are the dominant sources of BC, while in developed countries; emissions of BC are lower and are often dominated by transportation and industry. The use of increasingly clean technologies such as better cook stoves and emission controls on transportation and industrial emissions reduces the particle and BC emissions for a given activity. However, the increase in total energy use that accompanies development, as well as changing industrial development can offset some of the gains from these improvements.

On the global scale, fossil fuels and biofuels account for 66% and 34% of energy-related BC emissions, respectively. East and South Asia account for more than 50% of global energy related BC emissions. In their respective regions China and India account for most of the atmospheric burden. These emissions are from the transport sector and from biofuels which suffer from inefficient combustion. In addition, domestic coal combustion in East Asia accounts for a considerable fraction of BC emissions in this region. The contribution of different regions to the global burden follows the corresponding contributions to emissions. The largest contribution to the burden is from East Asia (37%) followed by South Asia (16%), Africa (14%), Europe (12%), North America (10%), South America (7%), west and central Asia (4%), Australia (<1%) and Oceanic regions (<1%). The relatively longer atmospheric residence time for African emissions results in a contribution of 14% to the global BC burden, compared to a contribution of 10% to emissions[10].

Global inventories are important for providing information on the distribution of BC emissions world-wide and for identifying key differences between regions, both in terms of total quantity of emissions and major sources. There are a few global BC inventories available currently, and the one from Bond et al.[11] is the most widely used and referenced. Compiling a global BC inventory is difficult for several reasons: varying emissions among similar sources, varying measurement techniques, and different PM

[10] Reddy, M. S., and O. Boucher (2007), Climate impact of black carbon emitted from energy consumption in the world's regions, *Geophys. Res. Lett.*, 34, L11802, doi:10.1029/2006GL028904.

[11] Bond, T.C.; Streets, D.G.; Yarber, K.F.; Nelson, S.M.; Woo, J.H.; Klimont, Z (2004). A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion; *J. Geophys. Res. Atmos 109*, D14203; doi: 10.1029/2003JD003697.

size cut points used in the measurements, and the definition of BC itself used in the inventories. Global BC and OC emission inventories are also complicated by a lack of detailed information on source types, emission factors, activities, and controls, especially in the developing world. Recent estimates of global emissions of BC and OC range from 8 to 24 terragrams (Tg) and 33 to 62 Tg per year, respectively. Thus, uncertainty is the hallmark of these studies, with emission estimates varying by a factor of 2 or more[12]. Bond et al estimated that the United States accounted for 5.6% (0.45 Tg/yr) of the global total.

In 2005, emissions of BC from U.S. sources total about 0.65 million tons (0.58 Tg), which represents about 8% of the global total. Mobile sources account for a little more than half (52%) of the domestic BC emissions. Nearly 90% of the mobile source total is from diesel sources. Open biomass burning is the next largest sources in the U.S., accounting for about 35% of the total. In general, BC is concentrated in urban areas, where populations are largest, making health an important issue in addition to climate in BC mitigation strategies (EPA, 2011). The degree of difference between the EPA inventory and Bond et al (2004) inventory for U.S. emissions is driven by EPA estimates for open burning and (to a lesser extent) for mobile sources in the U.S. that are higher than those from the global inventories. Wildfire emissions can vary greatly from year to year, and this may explain some of the difference between the estimates for open burning. Also, EPA estimates include all non-road and on-road emissions in the transportation source category, while global inventories group emissions from some of the smaller non-road sources into the Industry category. This could account for global inventory estimates of U.S. emissions being lower for transport and higher for industry compared to the EPA estimates.

California's emissions inventory for criteria pollutants and the U.S. National Emissions Inventory include PM emissions, which provide a basis for building a bottom-up BC and OC emissions inventory. BC and OC emissions can be estimated from source-specific PM2.5 emissions and the relative BC and OC fractions in the emitted PM. For an ARB-sponsored study by the Desert Research Institute[13], Chow et al. evaluated global and regional BC inventories and approaches for constructing a BC inventory for California. A black carbon inventory for California of 38,730 t/yr was comparable to the 33,280 t/yr estimated from a bottom-up global BC inventory. However, further examination showed substantial differences among subcategories. Most of the discrepancy was due to differences in open biomass burning (wildfires and agricultural waste) for which carbon emissions are highly variable. BC and OC emissions are sensitive to the availability and variability of existing source profiles, and profiles more specific to fuels and operating conditions are needed to increase emission accuracy.

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[12] Chow JC, Watson JG, Lowenthal DH, Chen LW, Motallebi N., (2010). Black and organic carbon emission inventories: review and application to California. J. Air Waite Manag Assoc. Apr;60(4):497-507.

[13] Chow, J.C., J.G. Watson, D.H. Lowenthal, L.W.A. Chen, (2009). Climate Change—Characterization of Black Carbon and Organic Carbon Air Pollution Emissions and Evaluation of Measurement Methods. Phase II: Characterization of Black Carbon and Organic Carbon Source Emissions. California Air Resources Board (Contract No.04-307). http://www.arb.ca.gov/research/apr/past/04-307_v2.pdf

Using a bottom-up approach, California emitted 52,084 t BC/yr during 2006. Among the sources, the largest single source was wildfires, 29% of total BC emission. The next two largest single sources were off-road mobile sources, 23% of the total BC emission, and on-road mobile sources, 20% of total BC emission (Table 1). Statewide OC emissions of about 107,979 tons/yr were twice BC emissions.

Table 1. BC and OC emissions (tons/year) for California in 2006 (Source: Chow et al.).

Source	BC	OC	%BC	%OC
Mobile (On-Road)				
Gasoline Powered	2,644	4,657	5%	4%
Diesel Powered	7,840	5,047	15%	5%
On-Road Total	10,484	9,704	20%	9%
Mobile (Off-Road)	12,158	13,890	23%	13%
Residential fuel combustion	4,004	17,422	8%	16%
Managed burning and disposal	7,374	19,652	14%	18%
Wildfires	15,161	29,530	29%	27%
Miscellaneous	2,903	17,781	6%	16%
Total	**52,084**	**107,979**	**100%**	**100%**

Note: percentage shows the variability of BC and OC fractions for major source types relative to the total BC and OC emissions, respectively.

California BC emission estimates were sensitive to the choice of source profiles. When a base-case diesel profile with a 50% BC abundance was replaced by one with an BC content of 26%, BC emissions from mobile on-road and mobile other (off-road) sources resulted in a 17% decrease in total BC emissions. The efficacy of the approach used to estimate BC and OC emissions in California depends on the accuracy and comprehensiveness of available PM emission factors, source activities, and BC and OC source profiles. Measurement techniques for BC and OC should also be standardized. These limitations need to be overcome to improve BC and OC inventories.

The starting point of all climate modeling studies of BC forcing is the emission inventory. However, Bond et al.[14] estimate that the global (and regional) emission inventory is subject to an uncertainty of about a factor of two, because of a lack of proper knowledge of emission factors, activity data, and technology splits. The regional contributions to atmospheric burden largely follow emissions from the respective regions. The emission of BC is quite dependent on the combustion process and emissions can vary significantly even among apparently similar sources. The need for a robust BC emission inventory that can capture some of these fine details is paramount. Studies are underway to test the emission estimates against currently available field observations; and we expect that iteration among emissions, atmospheric measurements, model results, and combustion tests will result in improved understanding of the magnitude of carbonaceous particle emissions.

[14] Bond, T.C. et al. (2007). Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000, Global Biogeochem. Cycles, 21, GB2018, doi:2010.1029/2006GB002840. http://www.sage.wisc.edu/pubs/articles/M-Z/Trautmann/BondetalGBC07.pdf

III. CLIMATE IMPACT OF BLACK CARBON IN CALIFORNIA

Recent work on climate change impacts in the western USA has focused attention on the shift in snowmelt timing toward earlier dates (Stewart et al.[15]), the shift from snow to rain (Knowles et al.[16]), the earlier onset of spring, and the effect that these changes will have on water supply in California and throughout the western USA. Pierce et al.[17] showed that about half of the observed decline in western USA springtime snowpack (1950–1999) results from climate changes forced by anthropogenic GHGs, ozone and particles. Although these trends in climate are largely attributable to increasing atmospheric concentrations of GHGs, recent modeling work has drawn attention to the role of soot (which is mostly BC) in modifying climate by reducing snow albedo. Hansen and Nazarenk[18] showed that soot may reduce snow and ice albedo in Northern Hemisphere land areas by as much as 3%, resulting in a climate forcing of +0.3 W/m^2. They found that due to positive feedbacks, the "efficacy" (change in air temperature per unit forcing) of soot is about twice that of CO_2. This indirect soot forcing may have contributed to global warming of the past century, including the trend toward early springs in the Northern Hemisphere, thinning Arctic sea ice, and melting land ice and permafrost. However, Hansen and Nazarenk (2004) also states that the substantial role inferred for soot in global climate does not alter the fact that greenhouse gases are the primary cause of global warming in the past century and are expected to be the largest climate forcing for the rest of this century.

The snowpack in the Sierra Nevada region is important to California's water resources. The high elevation snowpack serves as a natural reservoir that stores fresh water during the wet, cold season and releases it gradually during the dry, warm season. About 60% of the water supply for Southern California comes from melting Sierra Nevada snowpack. Snowmelt also affects hydropower generation in California (Vicuña et al.[19]). Snow albedo is among the most important local parameters in shaping the spatio-temporal variations in snowpack. Surface insolation and more specifically the portion of insolation absorbed by the snowpack is the leading energy source in the evolution of snowpack, especially during the melting period. Thus, variations in snow albedo can exert significant impact on snowpack during the course of accumulation and ablation. The surface albedo of sufficiently deep snowpack, and in turn the amount of

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[15] Stewart IT, Cayan D.R, Dettinger.M.(2005) Changes toward earlier streamflow timing across western North America. J Clim 18:1136–1155. http://tenaya.ucsd.edu/~dettinge/stewart_timing.pdf

[16] Knowles N, Dettinger M, Cayan D (2006) Trends in snowfall versus rainfall in the western United States. J Clim 19:4545–4559. http://tenaya.ucsd.edu/~dettinge/jclim_rain_v_snow.pdf

[17] Pierce DW, Barnett TP, Hidalgo H, Das T, Bonfils C, Santer B, Bala G, Dettinger M, Cayan D, Mirin A, Wood A, Nozawa T (2008) Attribution of declining western U.S. snowpack to human effects. J Clim 21:6425–6444. http://tenaya.ucsd.edu/~dettinge/swe_over_p_attribution.pdf

[18] Hansen J, Nazarenk L (2004) Soot forcing via snow and ice albedos. Proc Natl Acad Sci 101:423–428. http://www.pnas.org/content/101/2/423.full.pdf+html

[19] Vicuna, S., R. Leonardson, M. Hanemann, L. Dale, and J. Dracup. 2008. "Climate change impact on high elevation hydropower generation in California's Sierra Nevada: A case study in the upper American River." *Climatic Change* 87:S123–S137.

the insolation absorbed by the snowpack, depends largely on the ice grain size and impurities within or at the surface of ice grains (Waliser et al.[20]). There exist only a limited number of studies on the alteration in snow albedo and its impact on surface hydrology due to dust and BC particles deposited on snowpack. This is an important concern because the amount of BC deposition on snowpack is closely related with anthropogenic emissions. Thus, anthropogenic emissions that have bearing on the causes and characteristics of global climate change include an influence on local snowpack by altering snow albedo.

Hadley et al.[21] examined the concentration of BC particles in snow in California and the potential of these particles to reduce albedo and increase melt. Samples of falling snow and rain were collected at three locations in California: Central Sierra Snow Laboratory in the Sierra Nevada, Lassen Volcano National Park in the Southern Cascades, and at Trindidad Head on the Northern California coast. This study provides one of the first direct measurements for the efficient removal of black carbon from the atmosphere by snow and its subsequent deposition to the snow packs of California. The data reveal that BC concentrations in the Sierra Nevada snowpack are sufficient to perturb both snow melt and surface temperatures. The concentration of BC measured in the snow is consistent with recent model predictions for BC concentration in California mountain snow.

The associated reduction in snow albedo and reduced snow packs in early spring snowpack has been shown by regional climate models to be significant. All three stations reveal large BC concentrations in precipitation, ranging from 1.7 ng/g to 12.9 ng/g. The BC concentrations in the air after the snowfall were negligible suggesting an extremely efficient removal of BC by snow. The data suggest that below cloud scavenging, rather than ice nuclei, was the dominant source of BC in the snow. A five-year comparison of BC, dust, and total fine particle mass concentrations at multiple sites reveals that the measurements made at the sampling sites were representative of large- scale deposition in the Sierra Nevada. The relative concentration of iron and calcium in the mountain particle indicates that one-quarter to one-third of the BC may have been transported from Asia.

Coats[22] quantified the decadal-scale time trends in air temperature, precipitation phase and intensity, spring snowmelt timing, and lake temperature in the Tahoe basin, and related the trends to large-scale regional climatic trends in the western USA. It states that the Tahoe basin has abundant winter-time emission sources of BC. Many homes are heated with wood-burning stoves, and traffic during the ski season is heavy

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[20] Waliser, D.et al. (2009) Simulating the Sierra Nevada snowpack: The impact of snow albedo and multi-layer snow physics. California Environmental Protection Agency and California Energy Commission Report CEC-500-2009-030-F. http://www.energy.ca.gov/2009publications/CEC-500-2009-030/CEC-500-2009-030-F.PDF

[21] Hadley, O. L., Corrigan, C. E., Kirchstetter, T. W., Cliff, S. S., and Ramanathan, V. (2010). Measured black carbon deposition on the Sierra Nevada snow pack and implication for snow pack retreat, Atmos. Chem. Phys., 10, 7505-7513, doi:10.5194/acp-10-7505.

[22] Coats, R., (2010). Climate change in the Tahoe basin: regional trends, impacts and drivers. Climatic Change 102:435–466, DOI 10.1007/s10584-010-9828-3. http://escholarship.org/uc/item/6d8945fb;jsessionid=2E82C49ECFD9B1B34014A86494A7FA1F

at times. Air quality data are available for a station at South Lake Tahoe (SLT) and at Bliss State Park (BSP). SLT is the most urbanized area of the basin and had the highest elemental carbon concentrations, averaging 2.02 μg/m^3. BSP is less influenced by local sources, but like the rest of the basin is down-wind from major metropolitan areas in Sacramento Valley and Bay Area. The study indicates that atmospheric deposition of black carbon in the Tahoe basin may be implicated in the shift in snowmelt timing, increasing air temperature and the shift from snowfall to rain. Snowpack energy budget studies together with analysis of snowpack black carbon concentrations are needed to test this "snow albedo perturbation" hypothesis. Monitoring of black carbon in snow should be added to routine water quality monitoring in the Tahoe basin.

IV. GLOBAL WARMING POTENTIAL OF BC

Multi-gas mitigation strategies require metrics to compare the effect of emissions of different GHGs. Following its endorsement by the IPCC and its adoption within the Kyoto Protocol, the Global Warming Potential (GWP) has established itself as the metric of choice for the derivation of CO_2-equivalent emissions. GWP is a well-defined metric based on radiative forcing that continues to be useful in a multi-gas approach. Shortcomings have been identified; however, the scientific basis has not been fully established to address these shortcomings comprehensively in any currently discussed metric.

GWPs were meant to compare emissions of long-lived, well-mixed GHGs. Short-lived species, like BC, vary spatially and, consequently, it is very difficult to quantify their global warming forcing. Due in large part to the difference in lifetime between BC and CO_2, the relative weight given to BC as compared to CO_2 (or other climate forcers) is very sensitive to the formulation of the metric used to make the comparison. There is currently no single metric that is widely accepted by the science and research community for this purpose. The choice of a metric depends greatly on the policy goal. No single metric can be used to accurately address all the consequences of emissions of all the different climate forcers. The appropriate metric to use depends on factors such as: the time scale (20 years, 100 years, or longer), the nature of the impact (radiative forcing, temperature, or damages), concern over different processes (indirect effects, snow albedo changes, co-emissions), and whether sources and impacts should be calculated regionally or globally. The assessment of metrics will be included in the IPCC 5th assessment report (AR5; to be released around September 2013) process in an integrated manner with participation from all three working groups and the IPCC Task Force on GHG inventories. This process will likely include an assessment of numerical values for metrics that have been proposed in the literature.

It is important to note that different climate models could yield different results even if the same metric definition is chosen. Climate models are recently beginning to address the full effects of light-absorbing BC. However, estimates of the importance of carbonaceous particles as global warming agents vary greatly. Part of the variability between models is due to the inclusion or exclusion of certain physical effects, including

the nature of the mixing of absorbing BC aerosols with other, scattering aerosols, the multiple effects of aerosols on clouds, and the effects of BC on surface albedo. Differences also arise between models based purely on physical theory and those that attempt to fit observational data. An additional challenge in comparing model results is that different authors often present their results in different terms: some use the net radiative forcing (RF) of carbonaceous particles, others the RF of BC alone, and still others the net temperature change due to carbonaceous aerosols.

However, within bounded limits, there is no question that BC alters the Earth's energy balance, and is a net warming species. What is clear is that as scientists are able to disaggregate the effects of different particles, BC dominates so clearly and with such magnitude that it can no longer be ignored. The balance has now tipped in favor of taking action despite the remaining uncertainties on the exact metric to use.

While the IPCC 4th assessment report did not publish a GWP estimate for BC in its most recent report, independent estimates have been published in the peer-reviewed literature, including estimates drawn from IPCC report itself. Several leading scientists have reported estimates of the GWP for BC emissions from different sources. Most of the regional differences in GWP are caused by differences in the lifetime of BC. In general, we find in the published literature there are significant variations in the GWP values for BC emissions assigned to different regions. This indicates that BC emissions cause warming primarily in the region they are emitted, and that the role of BC in warming requires close attention to the geography of emissions.

Table 2 shows values from the literature for 100-year and 20-year GWP values of BC. As the table shows, BC's climate-forcing effect is generally very high (compared to CO_2, which by definition has a GWP of 1), and it is much greater when considered on a shorter time horizon like 20 years instead of 100 years. The table shows that generally the 20-year time horizon for BC is about 2000, whereas the 100-year GWP for BC is generally found to be more like 500 to 800. Overall, Table 2 indicates that BC is capable of generating warming that is two orders of magnitude greater than carbon dioxide. On a 20-year horizon, which places greater emphasis on rapid, near-term climate impacts, this BC warming is three orders of magnitude greater than the CO_2 warming.

Hansen et al. (2007) has calculated a GWP for fossil-fuel derived BC of 500, which includes both positive forcing from soot particles as well as the negative forcing from co-emitted OC. This value compares well with other published values: Bond and Sun (2005) calculated a GWP for BC of 680 for the same time horizon, but they did not include the effect of co-emitted species and cloud effects. The direct forcing of BC is significantly dependent on assumptions about how BC particles are mixed with other components of the particle population, with internal mixing tending to accentuate the positive forcing. BC also causes a complex set of impacts on cloudiness, including the so-called semi-direct effect, whereby changes in temperature and humidity structure due to the absorption of solar radiation by BC, alter the structure of clouds.

Table 2. Black carbon global warming potential values from research literature.

Source	Black carbon global warming potential		Indirect (cloud change) forcing
	100-yr	20-yr	
Hansen et al, 2007[23]	~500	~2000	Yes
Bond and Sun, 2005[24]	680	2200	No
Jacobson, 2007[25]	840-2240	2530	Yes
Reddy and Boucher (2007)[26]	480	--	No
Rypdahl et al, 2009[27]	830	2900	No
Fuglestvedt et al, 2010[28]	460	1600	No

Reddy and Boucher (2007) simulated the atmospheric cycle of energy-related BC from different regions and estimated the regional contributions to the global BC burdens and direct radiative forcing. The regional contributions of BC to global mean forcings closely follow the respective contributions to atmospheric burden in the form of PM. The GWP of BC for different regions ranges from 374 to 677 with a global mean of 480. Another variable that plays a role in the overall estimation of BC impacts is the albedo effect. The global mean indirect GWP due to the BC effect on snow albedo is estimated at 281. The indirect GWP due to the BC effect on snow albedo is estimated to be largest for Europe, suggesting that BC emission reductions from this region are more efficient to mitigate climate change. Rypdal et al (2009) also examined the regional differences in BC climate impact. The regions considered are EU17, Rest of Europe, Russia, North America, Latin America, East Asia, Centrally Planned Asia, South Asia, Japan, the Pacific OECD, Africa and the Middle East. The regional GWP values range from 640 to 1130 for the direct effect of BC. Most of the regional differences in GWP are caused by differences in the lifetime of BC, although up to 20% can be explained by differences in the RF per unit mass BC.

In general, we find in the published literature there are significant variations in the GWP values for BC emissions assigned to different regions. This indicates that BC emissions cause warming primary in the region they are emitted, and that the role of BC in warming requires close attention to the geography of emissions. We find Hansen et al. (2007) 100-year GWP of 500, which has been estimated globally, provides a reasonable estimate for use in calculating CO_2 equivalent benefits. Hansen's work is

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[23] Hansen, J., M. Sato, P. Kharecha, G. Russell, D. Lea, and M. Sidall.(2007). "Climate change and trace gases." Trans. R. Soc.. 1925, 1942. http://pubs.giss.nasa.gov/docs/2007/2007_Hansen_etal_2.pdf

[24] Bond, T. C. and H. Sun. 2005. "Can reducing black carbon emissions counteract global warming?" Environmental Science and Technology 39:5921–5926.

[25] Jacobson, M. Z. (2007). Testimony for the Hearing on Black Carbon and Global warming, House Committee on Oversight and Government Reform. See: http://oversight.house.gov/documents/20071018110606.pdf .

[26] Reddy, M. S., and O. Boucher (2007), Climate impact of black carbon emitted from energy consumption in the world's regions, *Geophys. Res. Lett.*, 34, L11802, doi:10.1029/2006GL028904. http://www.lmd.jussieu.fr/~oboImd/PDF/2006GL028904.pdf

[27] Rypdal, K., N. Rive, T. Berntsen, Z. Klimont, T. Mideksa, G. Myhre, and Ragnhild Skeie (2009). "Costs and Global impacts of black carbon abatement strategies." Tellus *61B, 625–641*. http://folk.uio.no/torbenm/central/Tellus_2009.pdf

[28] Fuglestvedt, J.S. and Shine, K.P. and Berntsen, T. and Cook, J. and Lee, D.S. and Stenke, A. and Skeie, R. and Velders, G.J.M. and Waitz, I.A. (2010) *Transport impacts on atmosphere and climate: Metrics.* Atmospheric Environment, 44, pp. 4648-4677. http://elib.dlr.de/68051/1/fugl-2010-4648.pdf

widely recognized and used in IPCC. Although, this should be considered a conservative estimate for fossil fuel BC forcing, as discussed by Hansen et al. (2007), because it assumes a high OC/BC ratio for fossil fuel emissions. Also it assigns 50% of the particle indirect effect (which causes cooling) to soot (BC/OC).

Hansen et al (2007) and Bond and Sun (2005) provide a 20-year GWP value for BC of 2000. Because BC particles produce a rapid, short-term, localized impact on the climate, we should also examine the climate effects using GWPs for a shorter time horizon. The 20-year GWP can be considered a means to control the rate of warming, while the 100-year GWP can be considered a means to control committed warming. Hence, reductions in short-lived pollutants like BC will make a significant contribution toward reducing the rate of warming, which is the basis for arguments that such reductions can buy time for future climate mitigation measures to be effective.

V. LIGHT-DUTY VEHICLE BC CLIMATE IMPACT

In developed countries, the BC problem is primarily associated with the high volume of fossil fuel use in transportation, particularly diesel. Chow et al. (2010) assembled data from about 800 PM2.5 source profile libraries and recent studies, and found that the highest BC abundances were found for on-road diesel vehicles and off-road diesel engines. In a study by Strawa et al (2010)[29], particulate emissions from motor vehicles inside a San Francisco Bay Area roadway tunnel (Caldecott) were characterized in 2004 and 2006. The amount of absorbing aerosol emitted and the low values of single scattering albedo indicate that particulate matter from motor vehicles exerts a positive (i.e., warming) radiative forcing and that the impact of medium/heavy duty diesel trucks is greater than light-duty vehicles. Another study by Kirchstetter et al (2008)[30] indicates that annual average BC concentrations in the Bay Area decreased by a factor of 3 over the 1967–2003 period, while diesel fuel use, the main source of BC emissions, increased by a factor of 6. The study also states that the contrast in the trends in BC concentration and diesel fuel use is striking, especially beginning in the early 1990s when BC concentrations began markedly decreasing despite sharply rising diesel fuel consumption. This contrast suggests that technology and fuel changes to reduce BC emissions have been successful.

Using data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) program, Bahadur et al. (2011)[31] examined the temporal and the spatial trends in the concentrations of BC for the past 20 years in California. Annual average BC concentrations in California have decreased by about 50% from 0.46 $\mu g\ m^{-3}$ in 1989

[29] Strawa, A.W.; Kirchstetter, T.W.; Hallar, A.G.; Ban-Weiss, G.A.; McLaughlin, J.P.; Harley, R.A.; Lunden, M.M. (2010). Optical and Physical Properties of Primary On-Road Vehicle Particle Emissions and Their Implications for Climate Change. *Journal of Aerosol Science* 41, 36-50.

[30] Kirchstetter, et al. (2008) Black carbon concentrations and diesel vehicle emission factors derived from coefficient of haze measurements in California, AE, 42(3): 480-491.

[31] Bahadur R., Feng Y., Russell L. M., Ramanathan V. (2011). Impact of California's air pollution laws on black carbon and their implications for direct radiative forcing. Atmospheric Environment 45, 1162-1167.

to 0.24 μgm^{-3} in 2008 compared to a corresponding reductions in diesel BC emissions (also about 50%) from a peak of 0.013 Tg Yr^{-1} in 1990 to 0.006 Tg Yr^{-1} by 2008. Bahadur et al. attribute the observed negative trends to the reduction in vehicular emissions due to stringent statewide regulations. Their conclusion that the reduction in diesel emissions is a primary cause of the observed BC reduction is also substantiated by a significant decrease in the ratio of BC to non-BC aerosols. The absorption efficiency of aerosols at visible wavelengths - determined from the observed scattering coefficient and the observed BC – also decreased by about 50% leading to a model-inferred negative direct radiative forcing (a cooling effect) of -1.4 Wm^{-2} over California.

California along with national and international climate-change policies have embraced a multi-gas approach where a "basket" of GHG emissions are considered together. In such a plan, emissions of each gas are given a weight relative to CO_2 so that multiple gases can be considered together. Sufficient scientific consensus exists on BC to provide appropriately accurate metrics on how to assess the climate value of actions to reduce BC emissions. Table 3 presents the climate impact of BC as compared with the other GHGs, and shows the product of the GWP and GHG and BC emissions. 2020 BC emissions are based on 3 mg/mi PM emissions, 66% BC fraction (500 $GWP_{100\text{-}yr}$; 2000 $GWP_{20\text{-}yr}$).

Table 3. Approximate illustration of equivalent CO_2 emissions from different GHGs for 2009 and for future (2020 and beyond) year new vehicles.

GHG emission	Global warming potential[a]		100-year gCO_2e/mile		20-year gCO_2e/mile	
	100-yr	20-yr	2009	Future (2020+)	2009	Future (2020+)
CO_2	1	1	337	<200	337	<200
AC refrigerant	1430	3830	6	0	16	0
CH_4	25	72	1.8	0.5	1.8	0.5
N_2O	298	289	0.1	0.03	0.3	0.05
BC [b]	500	2000	0.77	0.5	3.08	1.98

- [a] From IPCC 2007 fourth assessment review (AR4), except BC global warming potential estimate is based on ARB review of scientific literature. Pavley I used IPCC 2001 TAR GWPs values (e.g. 1300 for HFC-134a, 23 for CH_4, 296 for N_2O).
- 100-yr GWPs are IPCC 2007 AR4 (1,430 for HFC-134a, 25 for CH_4, 298 for N_2O) as used by U.S. EPA. 20-yr GWPs are IPCC 2007 AR4 (3,830 for HFC-134a, 72 for CH_4, 289 for N_2O.
- [b] Based on ARB's recent estimates: i.e., for the four vehicle types LDA, LT1, LT2, and LT3 the 2009 fleet average gasoline exhaust PM is 7.0 mg/mi; for 2020 it is 4.5 mg/mi assuming phase-in of the 3 mg/mi standard from 2017 to 2020 – with 0.22 BC/PM fraction for on-road gasoline from Chow et al[32]

[32] Chow, J.C., Watson, J.G., Lowenthal, D.H., Antony Chen, L.-W., Motallebi, N. (2011) PM2.5 source profiles for black and organic carbon emission inventories. Atmospheric Environment 45, 5407-5414.

We use two time horizons to estimate the climate impact: the short-term scenario is based on GWP for 20 years, and the long-term scenario is based on the more conventional 100-year GWP. Because BC aerosol exerts a rapid warming effect in the vicinity of the source, we think a 100-year weighted GWP for BC is less appropriate than a GWP based on a 20-year time. This shorter time horizon is better reflective of the speed at which control of, for example, soot emissions can benefit the climate relative to controlling carbon dioxide emissions. The two time frames can lead to a four-fold difference in CO_2eq emissions. Hence, a 20-year time frame gives a better perspective of the speed at which BC controls could benefit the atmosphere relative to CO_2 emission controls.

There is a wide range of BC and OC abundances in PM2.5 source profiles representing the same source type. The median PM2.5-BC abundance of 22% was used in Table 3 for on-road gasoline emission. As discussed earlier, Chow et al (2011) examined BC and OC abundances in source profiles from the U.S. EPA SPECIATE data base along with additional profiles obtained by the authors to evaluate their variability within and between source-types and to assess the effect of this variability on BC and OC emission rates. For profiles compiled in their study, BC and OC ranged 6-38% and 24-75% for on-road gasoline vehicles, and 33-74% and 20-47% for on-road heavy-duty diesel vehicles, respectively.

It should be noted that the introduction of new engine technologies (e.g., some types of gasoline direct injection) in recent model years has increased BC/PM ratios in some new gasoline-powered motor vehicles which may change the warming profile of emissions from these vehicles. More testing is needed to determine the typical ratios of EC/PM in LDV exhaust, as these ratios seem to be changing over time. These data can then be used, in combination with other vehicle fleet information, to more accurately estimate the atmospheric contribution of BC by LDV in climate models. The influence of BC on climate and public health in the future, and the need to pinpoint more precisely the effectiveness of various mitigation strategies for reducing BC, depend in large part on the magnitude of future emissions.

While uncertainties remain, emerging research suggests that targeting emission reductions from key sectors can have measurable benefits for both climate and public health climate. Mitigation of BC thus offers a clear opportunity: carefully designed programs that consider the full air pollution mixture (including BC, OC, and other co-pollutants) can slow near-term climate change while simultaneously achieving lasting public health benefits. Furthermore, currently available control technologies and mitigation approaches have already been shown to be effective in reducing BC emissions, often at quite reasonable costs. These mitigation approaches could be utilized to achieve further BC reductions.

VI. SUMMARY

BC is the light-absorbing carbonaceous fraction of PM that results from incomplete combustion of fossil fuels and biomass. BC causes warming primarily in the regions where it is emitted, and therefore merits analysis and solutions at the local scale. The ability of BC to absorb light energy and its role in key atmospheric processes link it to a range of climate impacts, including increased temperatures, accelerated ice and snow melt, and disruptions to precipitation patterns. Numerous national and international reports highlight the critical role of BC in climate change. The heightened interest in BC mitigation today is built on the well-recognized association of these emissions with localized air pollution and their severe negative health impacts. Any climate strategy for reducing BC emissions offers these important co-benefits.

BC is different from long-lived GHGs like CO_2 both in the variety of mechanisms by which it affects climate and its short atmospheric lifetime of days to weeks. This short lifetime, combined with the strong warming potential of BC, means that the climate benefits of reductions in current emissions of BC will be nearly immediate. It also makes reductions in BC emissions a potential near-term opportunity to postpone the effects of rising GHG levels on the global climate. In contrast, long-lived GHGs persist in the atmosphere for centuries. Therefore, reductions in GHG emissions will take longer to influence atmospheric concentrations and will have less impact on climate on a short timescale.

Because BC particles produce a rapid, short-term, localized impact on the climate, we should also examine the climate effects using GWPs for a shorter time horizon. The 20-year GWP can be considered a means to control the rate of warming, while the 100-year GWP can be considered a means to control committed warming. Hence, reductions in short-lived pollutants like BC will make a significant contribution toward reducing the rate of warming, which is the basis for arguments that such reductions can buy time for future climate mitigation measures to be effective. However, since GHGs are by far the largest contributor to current and future climate change, BC reductions cannot substitute for reductions in long-lived GHGs and that deep reductions in these pollutants are essential for mitigating climate change in the long run.

In conclusion, although there remains considerable uncertainty as to the magnitude of the effect of BC on the climate, mounting scientific evidence suggests that reducing current emissions of BC can provide near-term climate benefits, particularly for sensitive regions such as the Arctic. Because of its strong warming potential and short atmospheric lifetime, BC mitigation offers an opportunity to address key climate effects and slow the rate of climate change (i.e., reducing the risk of crossing thresholds with dramatic climate changes). Furthermore, currently available control technologies and mitigation approaches have already been shown to be effective in reducing BC emissions, often at quite reasonable costs. These mitigation approaches could be utilized to achieve further BC reductions. LDVs are currently a minor source of BC emissions compared to heavy-duty diesel engines. CARB anticipates that the stringency

of the proposed amendments to the existing PM mass standard will result in reduced BC emissions that can yield significant local and regional climate and health benefit.

VII. REFERENCES

1. Lukacs, H., et al., (2007). Seasonal trends and possible sources of brown carbon based on 2-year aerosol measurements at six sites in Europe. Journal of Geophysical Research e Atmospheres 112. http://publik.tuwien.ac.at/files/pub-tch_7878.pdf.

2. Yang, M.; Howell, S.G.; Zhuang, J.; Huebert, B.J. (2009). Attribution of aerosol light absorption to black carbon, brown carbon, and dust in China -interpretations of atmospheric measurements during EAST-AIRE. Atmos. Chem. Phys., 9(6): 2035-2050.http://www.atmos-chem-phys.org/9/2035/2009/acp-9-2035-2009.pdf .

3. Jacobson, M. Z., (2001) Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols *Nature, 409*, 695-697. http://www.stanford.edu/group/efmh/jacobson/Articles/VI/nature.pdf .

4. Watson, J.G., Chow, J.C., Chen, L.-W.A., (2005). Summary of Organic and Elemental Carbon/Black Carbon Analysis Methods and Inter-comparisons. AAQR 5, 65-102. http://aaqr.org/VOL5_No1_June2005/6_AAQR-05-06-OA-0006_65-102.pdf .

5. IPCC (2007), Working Group I: The Physical Science Basis, Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing, available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf.

6. Ramanathan, V. and Carmichael, G. (2008) Global and regional climate changes due to black carbon. Nature Geoscience 156, 221-227.

7. EPA (2011). Report to Congress on Black Carbon External Peer Review Draft. EPA-450/D-11-001, March 2011.

8. UNEP (2011). Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers.

9. Arctic Council (2011). Technical report of the Arctic Council Task Force on Short-Lived Climate Forcers**.** http://arctic-council.org/filearchive/ACTF_Report_22July2011.pdf .

10. Reddy, M. S., and O. Boucher (2007), Climate impact of black carbon emitted from energy consumption in the world's regions, *Geophys. Res. Lett.*, 34, L11802, doi:10. 1029/2006GL028904.

11. Bond, T.C.; Streets, D.G.; Yarber, K.F.; Nelson, S.M.; Woo, J.H.; Klimont, Z (2004). A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion; *J. Geophys. Res. Atmos 109*, D14203; doi: 10.1029/2003JD003697.

12. Chow JC, Watson JG, Lowenthal DH, Chen LW, Motallebi N., (2010). Black and organic carbon emission inventories: review and application to California. J. Air Waite Manag Assoc. Apr;60(4):497-507.

13. Chow, J.C., J.G. Watson, D.H. Lowenthal, L.W.A. Chen, (2009). Climate Change—Characterization of Black Carbon and Organic Carbon Air Pollution Emissions and Evaluation of Measurement Methods. Phase II: Characterization of Black Carbon and Organic Carbon Source Emissions. California Air Resources Board (Contract No.04-307). http://www.arb.ca.gov/research/apr/past/04-307_v2.pdf.

14. Bond, T.C. et al. (2007). Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000, Global Biogeochem. Cycles, 21, GB2018, doi:2010.1029/2006GB002840. http://www.sage.wisc.edu/pubs/articles/M-Z/Trautmann/BondetalGBC07.pdf

15. Stewart IT, Cayan D.R, Dettinger.M.(2005) Changes toward earlier streamflow timing across western North America. J Clim 18:1136–1155. http://tenaya.ucsd.edu/~dettinge/stewart_timing.pdf

16. Knowles N, Dettinger M, Cayan D (2006) Trends in snowfall versus rainfall in the western United States. J Clim 19:4545–4559. http://tenaya.ucsd.edu/~dettinge/jclim_rain_v_snow.pdf

17. Pierce DW, Barnett TP, Hidalgo H, Das T, Bonfils C, Santer B, Bala G, Dettinger M, Cayan D, Mirin A, Wood A, Nozawa T (2008) Attribution of declining western U.S. snowpack to human effects. J Clim 21:6425–6444. http://tenaya.ucsd.edu/~dettinge/swe_over_p_attribution.pdf

18. Hansen J, Nazarenk L (2004) Soot forcing via snow and ice albedos. Proc Natl Acad Sci 101:423–428. http://www.pnas.org/content/101/2/423.full.pdf+html

19. Vicuna, S., R. Leonardson, M. Hanemann, L. Dale, and J. Dracup. 2008. “Climate change impact on high elevation hydropower generation in California's Sierra Nevada: A case study in the upper American River.” *Climatic Change* **87**:S123–S137.

20. Waliser, D.et al. (2009) Simulating the Sierra Nevada snowpack: The impact of snow albedo and multi-layer snow physics. California Environmental Protection Agency and California Energy Commission Report CEC-500-2009-030-F. http://www.energy.ca.gov/2009publications/CEC-500-2009-030/CEC-500-2009-030-F.PDF

21. Hadley, O. L., Corrigan, C. E., Kirchstetter, T. W., Cliff, S. S., and Ramanathan, V. (2010). Measured black carbon deposition on the Sierra Nevada snow pack and implication for snow pack retreat, Atmos. Chem. Phys., 10, 7505-7513, doi:10.5194/acp-10-7505.

22. Coats, R., (2010). Climate change in the Tahoe basin: regional trends, impacts and drivers. Climatic Change 102:435–466, DOI 10.1007/s10584-010-9828-3. http://escholarship.org/uc/item/6d8945fb;jsessionid=2E82C49ECFD9B1B34014A86494A7FA1F

23. Hansen, J., M. Sato, P. Kharecha, G. Russell, D. Lea, and M. Sidall.(2007). “Climate change and trace gases.” Trans. R. Soc.. 1925, 1942. http://pubs.giss.nasa.gov/docs/2007/2007_Hansen_etal_2.pdf.

24. Bond, T. C. and H. Sun. 2005. “Can reducing black carbon emissions counteract global warming?” Environmental Science and Technology 39:5921–5926.

25. Jacobson, M. Z. (2007). Testimony for the Hearing on Black Carbon and Global warming, House Committee on Oversight and Government Reform. See: http://oversight.house.gov/documents/20071018110606.pdf .

26. Reddy, M. S., and O. Boucher (2007), Climate impact of black carbon emitted from energy consumption in the world's regions, *Geophys. Res. Lett.*, 34, L11802, doi:10.1029/2006GL028904. http://www.lmd.jussieu.fr/~obolmd/PDF/2006GL028904.pdf

27. Rypdal, K., N. Rive, T. Berntsen, Z. Klimont, T. Mideksa, G. Myhre, and Ragnhild Skeie (2009). "Costs and Global impacts of black carbon abatement strategies." Tellus *61B, 625–641*. http://folk.uio.no/torbenm/central/Tellus_2009.pdf

28. Fuglestvedt, J.S. and Shine, K.P. and Berntsen, T. and Cook, J. and Lee, D.S. and Stenke, A. and Skeie, R. and Velders, G.J.M. and Waitz, I.A. (2010) *Transport impacts on atmosphere and climate: Metrics.* Atmospheric Environment, 44, pp. 4648-4677. http://elib.dlr.de/68051/1/fugl-2010-4648.pdf.

29. Strawa, A.W.; Kirchstetter, T.W.; Hallar, A.G.; Ban-Weiss, G.A.; McLaughlin, J.P.; Harley, R.A.; Lunden, M.M. (2010). Optical and Physical Properties of Primary On-Road Vehicle Particle Emissions and Their Implications for Climate Change. *Journal of Aerosol Science* **41**, 36-50.

30. Kirchstetter, et al. (2008) Black carbon concentrations and diesel vehicle emission factors derived from coefficient of haze measurements in California, AE, 42(3): 480-491.

31. Bahadur R., Feng Y., Russell L. M., Ramanathan V. (2011). Impact of California's air pollution laws on black carbon and their implications for direct radiative forcing. Atmospheric Environment 45, 1162-1167.

32. Chow, J.C., Watson, J.G., Lowenthal, D.H., Antony Chen, L.-W., Motallebi, N. (2011) PM2.5 source profiles for black and organic carbon emission inventories. Atmospheric Environment 45, 5407-5414.