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Statement of
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before the

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I thank the committee for the opportunity to testify on the impacts of black carbon. I have been a researcher at NASA's Goddard Institute for Space Studies since 1995, and have taught the graduate level course on atmospheric chemistry and pollution at Columbia University since 1997.

Black carbon is one of many products of incomplete burning (combustion). It is not produced in large amounts from very high temperature combustion such as that which takes place in power plants, but in numerous types of much less efficient burning such as in diesel engines, agricultural and forest fires, and residential cooking stoves. Most of these emission sources are a direct result of human activities, while emissions from fires can be thought of as natural activities that are influenced by humans. The largest sources of black carbon emissions from human activities in the US (and Europe) are diesel engines while residential stoves (use for cooking and heating, and fueled by agricultural waste, wood, coal, dung, etc) and industrial processes are typically most important in developing countries and for the global total [1, 2].

Black carbon influences climate in multiple ways. It absorbs sunlight, leading to large-scale surface warming (though locally there may be cooling as less sunlight reaches the surface). It can also influence clouds in numerous, complex ways that are not fully understood at present. Hence the overall impact of those effects is not known. When black carbon falls on snow and ice surfaces it darkens them, reducing their ability to reflect sunlight away from the Earth's surface, and thus causing warming [3, 4]. Furthermore, the absorption of sunlight by black carbon particles on or in snow and ice leads to melting, creating a positive feedback that enhances the original warming effect substantially. A broad assessment of current scientific knowledge leads to a best estimate that black carbon causes substantial global mean warming, but with a very large uncertainty [5-12]. Near snow or ice covered regions, emissions of black carbon are almost certain to have an overall warming impact [3, 6].

Direct observations of the climate seldom reveal cause and effect, so that the influence of black carbon on surface temperature must be estimated by models. The models are continually tested against observations, however. NASA provides many useful measurements of atmospheric particulate (aerosols), including satellite observations, surface-based radiation detection networks, and airborne field campaigns in collaboration with other agencies such as the Department of Energy, the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation, as well as carrying out research and analysis, and modeling and data assimilation. Earth observing satellites with a direct role in observing aerosols include NASA's

Terra, Aura, Aqua and Calipso satellites (which include instruments from other US agencies and foreign partners) and NOAA's polar orbiting and geostationary environmental satellites. New missions in development are expected to make a direct contribution to the investigation of atmospheric aerosols, including the Glory satellite that should provide much more detail on aerosol properties than previously available, and longer range planning includes important follow-on capabilities. NASA ground based networks include the Aerosol Robotic Network (Aeronet) and the Micro-Pulse Lidar Network with sites located around the world. Developed primarily for satellite calibration and validation, these networks have proven to be useful and productive data sources for aerosol research as well. Annual NASA investment in aerosol missions and science has historically been approximately $130 million per year. As is described below, black carbon's role in climate cannot be understood in isolation, making it fitting that this research is embedded in a broader, multi-agency effort to understand the Earth's climate.

Multiple techniques have been used to investigate the effect of black carbon on surface temperature. In one type of study, emissions are put into a model of atmospheric chemistry and climate, and the results analyzed to isolate the effect of black carbon [6, 8, 9, 11]. The model is evaluated against observations both of particulate in the atmosphere and of climate. How well the model is able to reproduce measured particulate amounts and locations and observed temperatures gives us a sense of its accuracy and the credibility of its future projections. In addition to this type of study, changes in atmospheric energy fluxes that are due to particulate have been measured by aircraft and satellite and then put into climate models, and the response evaluated [10, 13]. Still another line of enquiry has used statistical comparisons between time-variations in climate model results and in observations to isolate the influence of black carbon in the surface temperature measurements [14]. A fourth, related technique has used regional temperature changes derived from the NASA Goddard Institute climate model and the observed regional temperature trends to calculate the influence of particulate on climate during the 20th century in comparison with other agents driving climate change [7]. Encouragingly, all these studies find results that are generally fairly similar, with an overall global mean warming due to black carbon that is about 15-55 percent of the warming due to carbon dioxide. These studies clearly still present a substantial range of values, and are further limited by our incomplete knowledge of interactions between black carbon and clouds but nevertheless all suggest a substantial warming impact from black carbon. It is important to keep in mind that while carbon dioxide increases have contributed more than any other single factor to warming, emissions of long-lived greenhouse gases other than carbon dioxide have in total contributed nearly as much to warming as has carbon dioxide itself [15]. At the same time, reflective aerosol particles such as organics, sulfates, and nitrates have offset a substantial portion of the warming from greenhouse gases [15]. This means that the percentage contribution of any individual factor to the total forcing of climate change depends upon how the comparison is made (against net forcing, or total positive forcing, for example). In terms of percent contribution to net warming since the mid-18th Century, the above estimate implies 15-55 percent of that warming may have been driven by increased black carbon (the contribution from carbon dioxide alone and the net warming from all climate change drivers has been approximately the same, so that comparison with either of these leads to comparable values). If the comparison is against the impact of all the greenhouse gases contributing to warming, then black carbon has added 10-35 percent to the greenhouse-gas induced warming, some of which has been offset by reflective aerosols and aerosol-induced cloud changes.

Black carbon has likely had even larger regional effects, especially due to its strong impact on snow and ice. In the Arctic, so called 'Arctic Haze' has been observed by pilots for decades, and results largely from transport of pollution from lower latitude industrialized areas. Though it is difficult to separate the effects of black carbon on Arctic temperatures from the effects of other factors, several results suggest that black carbon has contributed a larger share of warming in that region than it has globally [3, 6-8, 11]. In other words, more than 15-55 percent of Arctic warming since the mid 18th century might be attributable to black carbon. It may have had an especially large effect in the early 20th Century, when coal burning was commonly used in the Northeast US for residential heating, and along with reductions in sulfur emissions, may have also helped drive the very rapid Arctic warming of the past several decades [7]. In the Himalayan region, located very close to the world's largest emissions of black carbon, detailed observations of glaciers covering large areas and long periods of time are unfortunately quite sparse. While it seems that glaciers in this region are retreating overall [16], the role of black carbon in that retreat remains difficult to quantify, though it is likely to have played some role, especially in glaciers on the southern flank of the Tibetan plateau [17].

Since black carbon absorbs sunlight in the atmosphere much as it does in snow and ice, it can also affect other aspects of climate in addition to surface temperature. When sunlight is absorbed by the dark particles, the air a few kilometers above the surface containing the particles warms. This alters the temperature differences that create winds, which affects both regional temperatures and precipitation. Several studies have indicated that the large amounts of smoke and haze (so-called atmospheric brown clouds) observed near Asia can cause shifts in the timing and intensity of the monsoon, with large impacts for rainfall in India and China [18-20]. As with most aspects of climate change, it is difficult to verify this link exclusively with observations as many other factors also influence the monsoon, and other types of particles such as windblown desert dust contribute to the brown clouds. However, the physical mechanism linking black carbon to changes in precipitation is clear and operates worldwide. Unlike temperature changes, shifts in precipitation nearly always have negative net economic impacts as long-term infrastructure has quite sensibly been designed for norms over past decades.

Emissions of black carbon may affect the quality of the air we breathe as well as our climate. Policies are typically designed with the goal of limiting damage to one or the other, but largely treat the air quality and climate effects separately. For example, US regulations on the emissions of air pollutants including particulate matter (of which black carbon is a component) primarily consider their adverse effects on air quality public health, and the environment [21]. In most of the world, air quality regulations are created at local, state, or national levels, and do not consider climate impacts, while international climate change mitigation efforts (e.g. the Kyoto Protocol, the Copenhagen Accord) generally address greenhouse gases such as carbon dioxide but do not include shorter-lived pollutants such as lower atmospheric ozone or black carbon and does not consider the effects of the greenhouse gases on air quality. This separation is driven by policy rather than science, however, as the emissions of many pollutants affect both aspects of our environment. Encouragingly, research has shown that the optimal strategies to reduce black carbon and some ozone precursors are similar whether the goal is improving air quality or limiting global warming [22]. This is not the case for all pollutants that influence air quality, such as sulfur dioxide. However, for black carbon, carbon monoxide, volatile organic compounds and methane in particular, these two goals align. Even in the absence of a broad strategy encompassing both goals this argues for a stronger emphasis on reductions in emissions of these pollutants in air quality policies, for which there would be a climate co-benefit, and in climate policies, for which there would be an air quality co-benefit.

Actual policies will usually impact many species simultaneously, since, as discussed previously, black carbon is a product of incomplete combustion and this also produces substantial amounts of other particulates and gases. The amount of sunlight absorbed by black carbon can be substantially altered by interactions with these other compounds, and they themselves also affect climate. This means that it's necessary to examine the net effect of all emissions from a particular activity on climate rather than the effect of black carbon alone. Research suggests that strategies to simultaneously improve air quality and mitigate global warming differ from region to region. Preliminary results from ongoing work at my institute suggest that in the United States, reductions in overall emissions from diesel vehicles appears to be a method to achieve both goals, with a substantial part of the climate benefits coming from reduced black carbon. This could result from a shift from trucks to rail for cargo transport, for example. Imposition of diesel particulate filters on diesel vehicles, another method to reduce emissions, would in practice have different effects on emissions of different compounds. For example, these filters reduce particulate matter by about 90% but could result in a slight increase in carbon dioxide emissions due to decreased engine efficiency. Proper vehicle operation and maintenance practices optimize the air quality benefits of filters and other emission reduction technologies. The overall conclusion that such emissions reductions represent a win-win for air quality and climate does not change, however. More generally, increases in fuel efficiency coupled with reductions in emissions (carbon monoxide and volatile organic compounds) from both gasoline and diesel fueled vehicles show the most positive results for both climate and air quality [23, 24].

In contrast, many countries in the developing world use fuel with high sulfur content (as the US did years ago). Reductions in across-the-board emissions from those areas would improve air quality, but could actually increase near-term warming because these reductions would reduce reflective particles in the atmosphere that produce a cooling effect and increase atmospheric methane [24]. However, most of the developing nations are expected to follow the pattern of the developed nations and switch to low-sulfur fuels (to both directly reduce emissions that lead to particulate formation and to enable advanced emission controls) as their populations become more affluent and demand better air quality. While the transition to low-sulfur fuels may lead to near-term warming, simultaneous use of particulate filters would reduce that warming and may even lead to an overall cooling. In other words, policies that consider both air quality and climate, and hence strongly reduce emissions of black carbon, carbon monoxide and volatile organic compounds (as diesel filters do) as well as sulfur, are considerably more climate-friendly. In developing Asia, where particulate emissions are larger than in any other part of the world, reductions in emissions from both industrial processes and residential cooking stoves offer ways to simultaneously improve air quality and mitigate warming [24, 25]. Additional work is ongoing to characterize the effects of emissions from other activities, including aviation and shipping which may increase substantially and/or change location in the future. While there is more to learn, several things are already clear. Reductions in emissions of products of incomplete combustion will virtually always improve health. By targeting emissions rich in black carbon, carbon monoxide and volatile organic compounds relative to sulfur dioxide and nitrogen oxides, many options are available that will simultaneously benefit climate change.

It is worth noting that these options are by no means the default choices, and to date air quality regulations made for the sake of public health in the US, Europe and Japan have often been much more successful in reducing pollutants that cool climate (sulfur dioxide and nitrogen oxides) than those which lead to warming (for example, methane and black carbon). Changes in emissions of short-lived pollutants resulting from air quality policies along with the continued growth in Northern Hemispheric emissions of some warming pollutants such as black carbon have been linked to the accelerated warming of the Northern Hemisphere since the 1970s and the very rapid heating of the Arctic during recent decades (they may account for more than half the 1970-2007 warming trends, which have been nearly two degrees F (1 C) for the Northern Hemisphere and 3 F (1.5 C) for the Arctic)[7]. This highlights the substantial impact of these pollutants on climate change, especially at regional scales. It also emphasizes the importance of coordinated air quality and climate policies to achieve progress in both areas simultaneously rather than continuing our record of improvement in one at the expense of the other.

The health benefits that could be gained from particulate and ozone precursor emissions reductions are clear from epidemiological studies. These studies span both long periods of time and wide areas and also short, local changes due to events such as temporary industrial strikes [26-30]. Both particulate matter and tropospheric (lower atmospheric) ozone, a gas produced from carbon monoxide, volatile organic compounds and methane (in the presence of nitrogen oxides), contribute to a variety of adverse health effects. Reductions of emissions directly into living spaces are likely to yield substantial health benefits. One recent study estimated that roughly 2 million deaths could be prevented in India by bringing advanced biomass stoves to 15 million homes per year over the next 10 years [31]. While the health benefits of emissions reductions are most strongly felt in the nearby population, long-range transport of air pollution can also be substantial: one recent study found that ozone levels a few kilometers above the Western US can be significantly influenced by emissions from East Asia [32]. Another recent study estimates that the difference between Chinese emissions of particulate following a 'high-end' or 'low-end' projected trend would be several hundred premature deaths annually in the US in 2030 [33]. Though small compared with the hundreds of thousands of additional premature deaths within China itself, this nonetheless shows that the health impact of air pollution is not simply a local issue. Climate impacts extend even more broadly, with most of the Northern Hemisphere north of the tropics responding strongly to emissions from anywhere within that region, for example [7]. In a study of the projected climate during the 21st Century, substantial warming and drying of the continental interior of the US was seen, and much of this was driven by changes in air quality pollutant emissions from East Asia [34].

There are other co-benefits from control of air pollution in addition to improved public health. Particulate matter and tropospheric ozone precursors both impair visibility, with potential detrimental economic impacts on tourism and recreation. Elevated levels of tropospheric ozone also causes damage to plants, leading to economic losses from reduced agricultural and forestry yields [35]. Air pollution can also degrade many types of materials used in buildings, such as stonework and metalwork. In economic analyses developed by the EPA and others, the valuation of human health impacts tend to dominate, however [35]. Economic analyses including the benefits of reduced pollution of course show vastly different net economic impacts of controlling emissions from incomplete combustion than estimates based simply on the cost of implementing the controls. This is true even without including any monetary value for reduced damages due to climate change. A compelling example of the use of co-benefits to motivate a strategy to mitigate emissions that lead to warming is the international 'Methane to Markets' program led by the United States. This program has provided funding and expertise to advance projects that capture methane from farms, landfills, pipelines and coal mines. The projects then use the captured methane to produce energy at a net profit while also mitigating warming. When the economic benefits from avoided health impacts are included, many projects to control black carbon and carbon monoxide may have higher benefits than costs even without including the value of reduced warming. For example, recently proposed emissions regulations for diesel vehicles in California were estimated to lead to a reduction in human health damages of approximately five times the cost of implementing the particulate reductions[36]. Numerous federal diesel rules have shown similar and even greater ratios of health benefits to costs. Policies that consider both human health and climate change mitigation simultaneously are likely to provide substantial health benefits in associated health care cost savings[37]. In the US alone, air pollution has been calculated to lead to 70-270 billion dollars in damages per year [35], so that there is a great deal of potential for co-benefits that should be considered when evaluating the costs of emissions reduction.

Reducing emissions of the short-lived warming agents is unlikely to eliminate global warming even in the near-term, and reductions in carbon dioxide emissions are clearly required to mitigate long-term warming. However, the combined influence of all the short-lived warming agents, black carbon, carbon monoxide, volatile organic compounds, methane and hydrofluorocarbons, is quite large, so that reductions in all these together could achieve a substantial reduction in near-term warming. With the exception of the hydrofluorocarbons, all these reductions would lead to significant improvements in air quality as well, making them attractive options from many perspectives. And for all these short-lived forcing agents, technology to reduce emissions is already readily available for deployment, with the primary barriers being structural rather than technological (unlike, for example, carbon dioxide produced from burning fossil fuels).

Further research is needed to provide a clearer understanding of how much black carbon is emitted by different types of burning, how it interacts with other types of particulate and with clouds, and how to improve the ability of models to simulate black carbon in the atmosphere and cryosphere (snow and ice). Such research would lead to more reliable estimates of black carbon's role in climate change. However, taking into account the current range of estimates for black carbon's global impact, along with its known ability to substantially influence snow and ice covered regions and to shift precipitation, emissions reductions are likely to be a useful component of strategies to mitigate climate change. Realistic emissions reductions would affect several types of particles and gases, and thus require careful analysis of their net impact. This type of research, that integrates knowledge of many different aspects of the climate system, is needed to compliment federal programs that are typically focused on single components of climate research. Ideally, future research should provide policy makers a menu of mitigation options covering technological, structural and behavioral, and regulatory approaches for individual emission sources in different regions of the world. As stated earlier, reductions in emissions from incomplete burning are virtually always good for health. Reductions of emissions rich in black carbon, carbon monoxide, volatile organic compounds and methane are typically good for climate as well, allowing many 'no regrets' options to be identified already. Further work can allow much better optimization of emission reduction strategies to simultaneously provide clean air and limit climate change.

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