A Detailed Study of Black Carbon and its Regional Impacts

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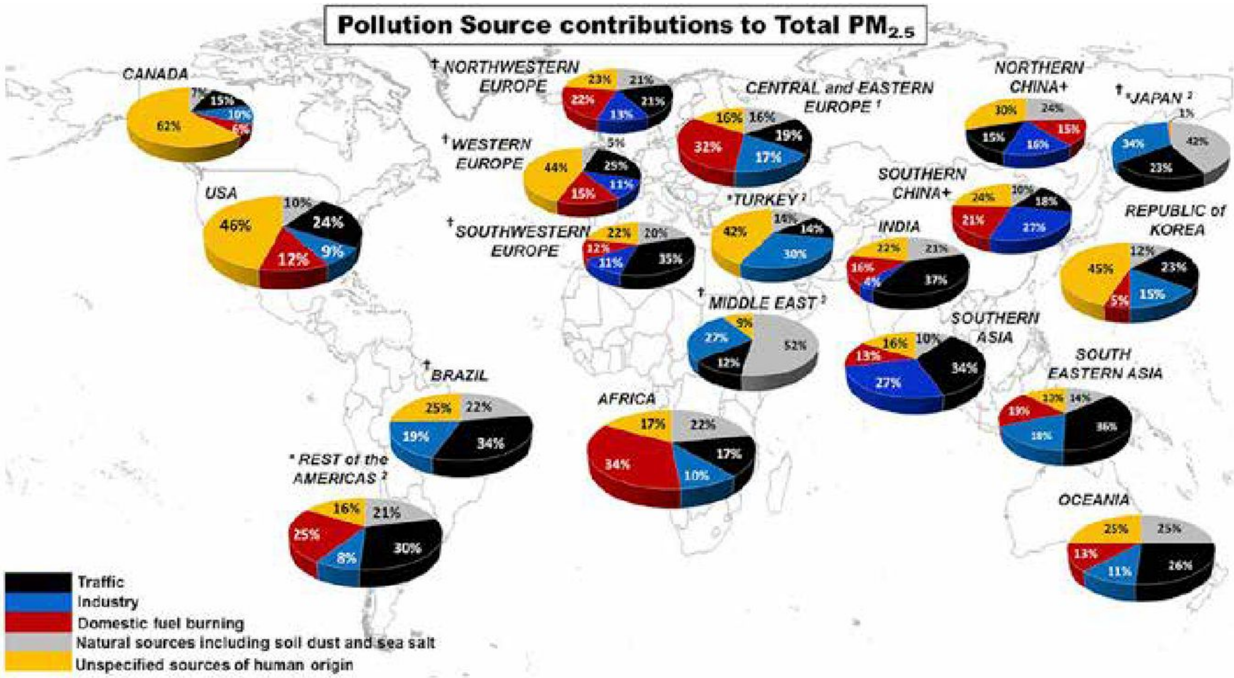
Abstract:

Black carbon (BC), is a residual particle that is released due to the incomplete combustion of fossil fuels, biomass and biofuels. Black carbon is the light-absorbing part of soot that is present in the atmosphere, which absorbs on an average 100,000 times more energy per BC particle than a CO_2 molecule does. Though it is classified as a short lived climate pollutant, the effects of BC on the environment are translated into long term repercussions. The high absorptivity of BC has caused the increase of melting of snow as it settles into snow and increases the heat being absorbed on the surface of snow. It causes indirect, and semi-direct effects in cloud which change global weather patterns. The particulate nature of BC causes it to settle into the human lungs and cause various respiratory diseases affecting 4.3 million people per year reported by WHO. Black carbon also augments the formation of tropospheric ozone which is a pollutant in the atmosphere. This has direct effects on the agricultural sector. This presentation undertakes a study on the connection of household wood based cookstoves and their direct effect on the contribution to the increasing content of BC in the atmosphere. This presentation also talks about the environmental and atmospheric impact after the reduction of BC. This paper establishes a relationship between solar cookers, wood cookstoves and the amount of BC with a regional focus. This relationship helps us understand the impact of solar cookers to the atmosphere in the context of BC quantities.

Introduction:

Black carbon (BC) is a residual particle that is released due to the incomplete combustion of fossil fuels, biomass and biofuels and forms a part of particulate matter (PM). BC is a type of particle that is emitted directly into the atmosphere and is emitted when there is insufficient oxygen and heat available for the combustion process to burn the fuel completely. All carbonaceous by-products of combustion fall under the particulate matter class $PM_{2.5}$ The broad categories of fuel utilization are traffic, industry, domestic cooking and other miscellaneous activity. Worldwide, more than three-quarters of the black carbon produced is thought to come from developing countries, generated from cook stoves, open burning, and older diesel engines. Nearly 2.8 billion people worldwide cook primarily with solid fuels. From the diagram below, we can see that domestic fuel burning is the major cause of BC, especially in Africa, south America and parts of central Europe.



Source: REDUCING GLOBAL HEALTH RISKS Through mitigation of short-lived climate pollutants, WHO (2015)

Discussion:

BC has been classified as a Short Lived Climate Pollutant (SLCP) where the activity of the particle in the atmosphere is marked from days to years. Black carbon specifically remains in the atmosphere for days, which was why studies of the matter were not taken seriously. Though it’s activity may act only for a few days, black carbon has the capacity to absorb all wavelengths. Carbon dioxide can only absorb from wavelengths in the IR region which is only a portion of the wavelength spectrum. That makes BC absorb 1,000,000 times more energy per unit mass than carbon dioxide does. Recent studies have also shown that the reaction of soot (containing BC) with nitrogen dioxide results in the formation of nitrous acid (HONO). Nitrous acid is a source of the most important daytime radical- the hydroxyl (OH) radical. The OH radical is one of the key species in photochemical cycles responsible for ozone formation, which can lead to the so called "photochemical smog" in polluted regions. This shows that the effects of BC persists in the atmosphere longer than a few days and thus changes the atmospheric relevance of soot.

As black carbon has high absorptivity, it's relevance in the atmosphere is high. The black carbon suspended in the atmosphere absorbs the energy and thus consequently heats the atmosphere. Most of the infrared rays from the sun pass through the atmosphere, reach the earth's surface and are emitted back and some of the emission is absorbed by greenhouse gases like carbon dioxide and methane. The gases re-emit the absorbed radiation with half returning to the earth's surface at the lower atmosphere. Hence increasing the amount of BC in the atmosphere increases the warmth as black carbon acts as greenhouse gases (GHGs).

The BC that is present in the atmosphere can settle down onto snow, glaciers and ice packs. Light absorptivity of BC increases the heating of snow and ice, which accelerates melting of snow and ice. BC was also identified in arctic snow by Clarke and Noone. This has led to increased melting of the glaciers in the Arctic and the Himalayas which has contributed to the rising sea levels. The content in the atmosphere of the Arctic mimics that of urban aerosols; this phenomenon is called arctic haze. This comparison concludes that the snow-capped regions of the Arctic are also in danger of melting as the heat in the atmosphere increases. Within the Himalayas, BC may be responsible for as much as 50% of the total glacial retreat.

The BC is a component of particulate matter. It remains airborne and sometimes condenses along with water molecules to form a part of brown clouds in the atmosphere. BC also alters the properties and distribution of clouds, affecting cloud reflectivity and lifetime (indirect effects), stability (semi-direct effect), and precipitation. These impacts are associated with all ambient particles, but not GHGs. The clouds containing BC inclusions in water drops and BC in between water drops can absorb some IR emitted from the earth's surface, reducing the quantity that is reflected. This is termed as the first indirect effect or the cloud albedo effect. Clouds tend not to accumulate together, which reduces the precipitation chances and increases the lifetime of the clouds. This has been called the "second indirect effect" or the "cloud lifetime effect". In certain kinds of "mixed-phase clouds" which contain clouds with both ice and water, smaller droplets cause a delay in the freezing of the droplets, changing the characteristics of the cloud; however, the IPCC was not able to determine whether this "thermodynamic effect" would result in overall warming or cooling. The semi-direct effect refers to the heating of the troposphere by absorbing aerosols, affecting the relative humidity and stability of the troposphere, which in turn affects cloud formation and lifetime. There has been a recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. This means that there is a change in the climatic zones of the earth. This changes the vegetation, climate and ecosystems of the areas in the northern hemisphere.

BC has impacts on the human health system as well, especially in the respiratory regions. Since it is particulate in nature it rests in the lungs. According to WHO 4.3 million premature deaths each year equivalent to 7.7% of global mortality, which is more than the toll from malaria, tuberculosis and HIV/AIDS combined. BC causes one quarter of all global deaths from stroke, 17% of adult lung cancer deaths, and 15% of deaths from ischemic heart disease. It is also responsible for almost one third of all deaths from chronic obstructive pulmonary disease (COPD) in Lower Middle Income Contries (LMICs). Research also claims prenatal air pollution exposure causes cardiovascular diseases when they become young adults.

Black Carbon in the atmosphere can both negatively interfere with plant growth and agricultural productivity. BC reduces the amount of solar radiation available for photosynthesis. BC also causes solar dimming which is an effect that reduces the amount of solar energy reaching the earth's surface.

It is estimated by the WHO that around 2.7 billion people worldwide cook using biomass fuel, most of which are poor and in developing countries. Cook stove emissions not only create indoor exposures but also contribute to direct air pollution through indirect venting (exchange of air between the outside and inside) and direct, active venting (i.e., chimney) to the outdoors. Open-design cook stoves are a type of cookstove where combustion byproducts are expelled directly into the indoor environment, resulting in high concentrations of pollutants inside the home. These emission factors for BC can vary by 5–6-fold depending on stove design and fuel type. In addition, the BC mass-ratio component of PM under 2.5 μm in diameter ($PM_{2.5}$) has been shown to vary using laboratory-based test burns of different stove designs.

While laboratory-based studies are valuable for estimating stove emissions, climate modeling requires estimates of household emissions. The study of cookstove emissions from a home requires a study of the PM emitted from the house. Only a fraction of PM emitted indoors during combustion will settle and deposit on indoor surfaces, while the remaining will exfiltrate to the outdoor environment. Studies translating laboratory-based cookstove emissions to ambient emissions from a house often use hypothetical air exchange and particle deposition rates resulting in fractional exfiltration estimates. Furthermore, measurement of air-exchange rates from housing in developing countries is extremely limited.

There are various models that exist based on experimental data, to quantify the effect of BC. But there has been disputes amongst scientists as these experimental data varies from experiment to experiment. The defined metric is the Global Warming Potential (GWP). The definition of the GWP by the IPCC (2007) is
"An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame." There are other systems like the Global Temperature Potential (GTP). But there is no fixed system for BC as the range for quantification of black carbon is wide. For one ton of BC is equal to 48 tons to 4600 tons of carbon dioxide. This range is very broad due to the fact that BC is more stagnant in the atmosphere than carbon dioxide is. Since GWP is an experimental parameter, different studies and experiments in different parts of the world result in different statistics. Nonetheless, this means that the effect of BC is at least 48 or more times in effect of carbon dioxide.

Calculations:

The amount of BC in the air is 4.78 μm/m^3 and 50% comes from the biomass burning out of which two-thirds is due to firewood cookstoves. This amounts to 1.593 μm/m^3 in the atmosphere due to wood based cookstoves in the Indian subcontinent, this affects the Himalayan region and the melting of the ice-caps.

Global Warming Potential is the amount of radiative heat energy produced by 1 kg of the species and is a standard metric to measure how much a gas contributes in comparison to CO_2 which is an established GHG. That is the potential of heat to contribute to the warming of the planet. Thus, BC has the potential, in the Indian subcontinent, to warm the atmosphere by 1.0834x10^{-6} W/m^2 of heat energy. In comparison to the CO2 produced in the region, which can heat up the area by 5.33x10^{-15} W/m^2 of heat energy. That means that black carbon produced by the wood based cookstoves can heat up the atmosphere 2.1x10^8 times more than the CO_2. This implies that BC from fire wood based cookstoves can heat up the environment 100,000,000 times more than what CO_2 does which is a known GHG that contributes to the warming up of our planet.

Thus we can conclude that by using solar cookstoves, we can reduce this BC emissions which therefore reduce the glacial meltings in the Himalayas. We see how detrimental BC is to the heating up of the atmosphere especially in context to carbon dioxide which is a popularly known GHG.

Conclusion:

Eliminating BC could eliminate 20–40 % of the global warming over a period of 3–5 years. On the other hand, reducing CO2 emissions by a third would have the same effect but only after 50–200 years. BC in global climate change, Ramanathan and Carmichael (2008) have suggested that the BC forcing is the second most important contributor to global warming, after CO2 emissions. Since BC has an average residence time in the atmosphere of a few days to weeks relative to greenhouse gases which range from years to centuries, mitigating BC emissions to combat climate change can produce almost immediate effects in terms of reduced radiative forcing, subsequently producing direct benefits for public health.

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