



IEAGHG Information Paper 2014-IP17: Black carbon – a double-edged sword?

The motivation of this IP is to inform about the opposing effects black carbon (BC) might have on climate change and global warming. The background are some recently published articles, in particular by Hodnebrog et al.¹ and by Bond et al.², revealing that BC's environmental effects and the issues surrounding it appear to be rather complex.

First of all, there is no stringent or consistent definition of BC throughout the literature, and this can cause a certain lack of comparability among studies. A lot of references simply refer to BC as particulate matter (PM), sometimes adding “fine” and/or “ultra-fine” to the description. The US Environmental Protection Agency (EPA) defines BC as the most strongly light-absorbing fraction of particulate matter formed by incomplete combustion processes and mainly consisting of so-called fine particles with a diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}). Other sources, like Bond et al., rely on a definition that is based more on a combination of unique characteristics of the particles. These properties are: strong visible light absorption of at least $5 \text{ m}^2/\text{g}$ at 550 nm, refractory with vaporization temperature near 4000 K, aggregate morphology, and insolubility in water and common organic solvents. It is this combination that distinguishes BC from other light absorbing material, such as some organic carbon compounds (e.g. planar graphite, dust, brown carbon).

So let's now move on to the contribution of BC to global warming. The direct effect relates to absorption of solar radiation, and there is a high certainty that this effect causes a net positive change, i.e. warming. Semi-direct and indirect effects are mainly due to alterations of clouds and the temperature structure of the atmosphere. These processes have a high degree of complexity and feedback. Thus, they may have either positive or negative effects on climate forcing. At present, even the sign of BC ice-cloud forcing, for example, is unknown.

Total global BC emissions are around 7,500 Gg/yr but might be a factor of two or three higher when correction with information from remote sensing is included. The predominant sources of BC are combustion processes: fossil and biomass fuels for transportation (e.g. diesel engines), industrial and residential uses, as well as the open burning of biomass (BB). Fig. 1 gives an overview of BC emissions and sources in 2000.

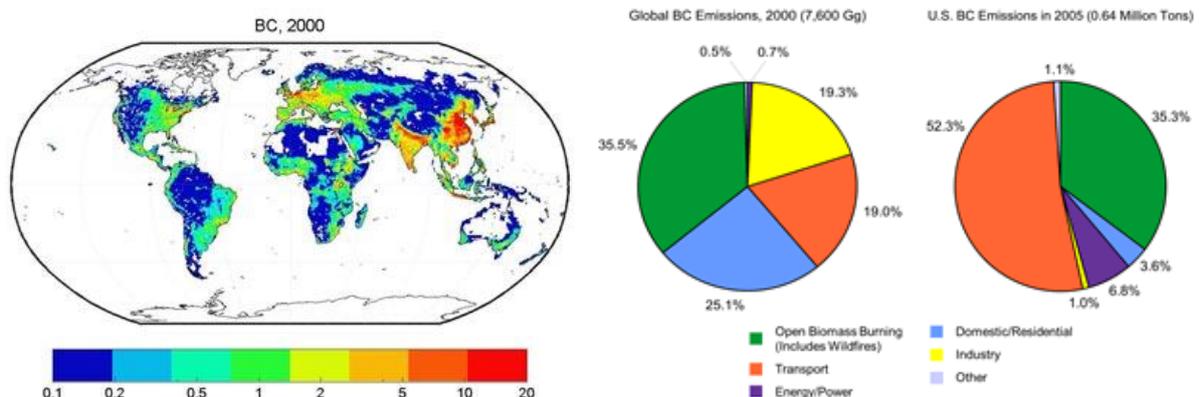


Fig. 1 Total global BC emissions in 2000² (left) and BC source categories³ (right)

¹ Hodnebrog, O; Myhre, G; Samset, BH. How shorter black carbon lifetime alters its climate effect. Nature Communications. 5:5065, DOI: 10.1038/ncomms6065, www.nature.com/naturecommunications.

² Bond, TC et al. Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research: Atmospheres. Vol. 118, 5380–5552, doi:10.1002/jgrd.50171, 2013.

³ Lamarque et al., 2010 and US EPA, <http://epa.gov/blackcarbon/basic.html>



The importance of BC with regards to the climate system originates in its properties: it absorbs solar radiation, influences cloud processes and alters the melting of snow and ice sheets. Therefore, effects of BC are more than just the direct radiative forcing alone.

Other chemicals and aerosols present during measurement of BC concentrations in the atmosphere can distort the results (by up to 80%). These other components, such as organic matter and sulphur species, also affect the atmospheric properties of BC, i.e. how it interacts with clouds, absorbs light and how quickly it is removed from the atmosphere. This means they can influence both the sign and the magnitude of net climate forcing of BC-rich emissions sources. The scientific understanding of the behaviour and effects of these aerosol mixtures is still in its infancy.

Bond et al. give an estimate of 900 for the 100-year global warming potential (GWP) of BC but note that the range could be anything between 120 and 1,800 due to all the related uncertainties.

In contrast, a recent study by Hodnebrog et al. found that climate impact of BC is overestimated. The researchers from the Center for International Climate and Environmental Research-Oslo (CICERO) present modelling results in *Nature Communications* that indicate the global warming effect of BC was significantly overestimated in past models. The climate effect of BC also depends on the altitude, so the higher the altitude the stronger the radiative forcing. Most models assume too much BC in the upper part of the atmosphere. To add complexity, BC can have different warming, or even cooling, properties depending on atmospheric conditions, such as altitude, moisture, and cloud cover. In conclusion, the researchers found strong cooling effects, with the net effect still being positive, i.e. warming but the extent being much less than assumed in the past.

The main reason for the overestimation of BC's effect on global warming is most likely an overestimation of the lifespan of BC in the atmosphere. At the same time, there appears to be an underestimation of global BC emissions, especially from domestic fuel use in Asia and Africa, and from gas flaring practices in Russia, Nigeria and the Middle East. So Hodnebrog et al. doubled the BC emissions in their model while simultaneously reducing the lifespan, based on recent observational evidence, by 40% compared to standard models. Even with accounting for higher real-world BC emissions, they found that the direct aerosol effect remained unchanged. From this, they drew the conclusions that direct and semi-direct effects approximately cancel out for altitudes higher than 500 hPa. However, further confirmation and validation of this results is necessary. The authors note it is crucial to have accurate representation of clouds and vertical profiles of BC emissions to determine the net effect on global warming correctly. This area is still connected with high uncertainties and needs further understanding and quantification. The authors suggest it might be a good idea to focus on CO₂ mitigation options, rather than short-lived climate pollutants (SLCP), like BC, to reduce global warming. This is backed-up by a very recent paper by Rogelj et al.⁴, stating that the 2°C scenario will be largely unaffected by SLCP-related measures, so any SLCP measures are complementary rather than a substitute for early CO₂ mitigation.

A different message came from the comprehensive 173-page paper by Bond et al. in 2013. The authors found that the global atmospheric absorption attributable to BC is too low in many models and thus suggested to increase it by a factor of three. However, Bond et al. acknowledge the substantial uncertainties related to net climate forcing of black carbon, which are mainly due to the not fully understood BC-cloud interactions. The authors present a value for the total climate forcing of BC that is higher than the value the IPCC advocates because they have included effects the IPCC did not consider (e.g. BC from biofuels and open biomass sources, certain cloud processes). The paper also contains the same conclusion as Hodnebrog's article, namely that modelling and observation of the vertical profiles of BC emissions is poor and needs further research.

⁴ Rogelj, J et al. Disentangling the effects of CO₂ and short lived climate forcer mitigation. *PNAS Early Edition*. October 2014. www.pnas.org/cgi/doi/10.1073/pnas.1415631111



So let's assume for a second that the total global warming effect of BC-rich emission sources might be negative, or at least neutral. Is it already time to breathe a sigh of relief? Maybe not, if we look closely at the photographs taken by Jason Box (Geological Survey of Denmark and Greenland) and his research colleagues during a field trip to Greenland this summer⁵. The photos, see Fig. 2, clearly demonstrate the ice in Greenland is record-setting dark.



Fig. 2 Dark ice on Greenland's ice sheet (photos by Jason Box)

Box and his team measured the dark ice in 2014 has increased 5.6 % compared to last year. This is the highest value anyone has ever measured, and the additional absorbed energy is equivalent to approximately twice the current US annual electricity consumption. Because of this, the Greenland ice sheet is likely to melt much quicker, as Fig. 3 shows.

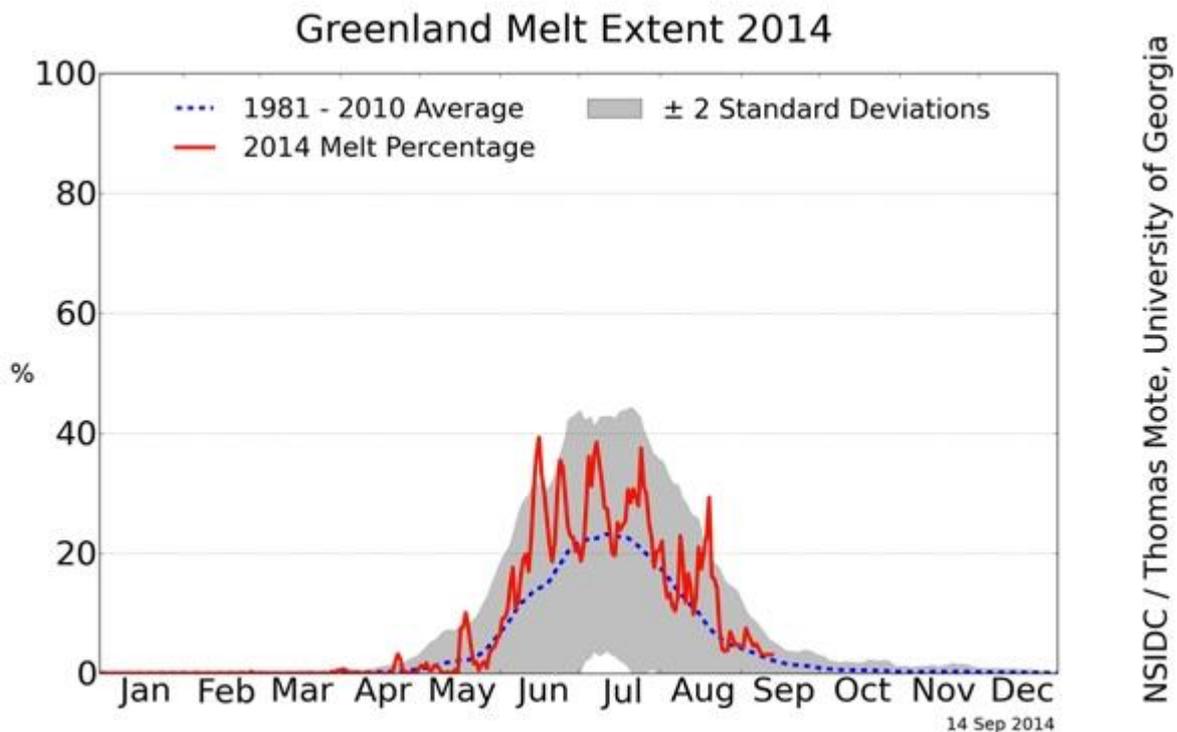


Fig. 3 Greenland ice sheet melt extent in 2014 compared to 1981-2010 average⁶

⁵ For more background information and photos about Greenland's dark ice, please visit the website of Jason Box's crowd-funded research project „Dark Snow“: <http://darksnow.org/>.

⁶ Courtesy of The National Snow and Ice Data Center.



According to Box, there are several explanations for the increasing darkness of the ice in Greenland: microbial activities (ice algae), wind-blown dust/dirt, increasing temperatures and BC from domestic and industrial uses as well as forest fires. It still remains a challenge to attribute the BC found in the ice to specific emission sources. However, BC from forest fires leads us directly to an interesting “coincidence”: 2014 was also the year with the highest amount of forest fires ever recorded in the Arctic, as you can see in Fig. 4.

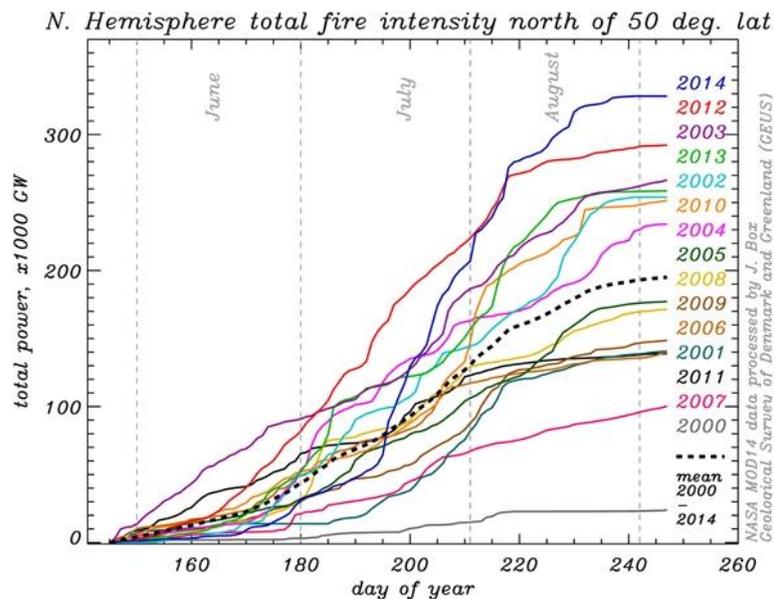


Fig. 4 Total fire intensity of Northern Hemisphere fires from 2000 to 2014⁷

Fig. 4 also indicates that the rate at which Arctic fires have been burning over the last three years has almost doubled compared to the rates a decade ago. Although Jason Box has not published his results in a peer reviewed journal yet (he plans doing so later this year), they are in agreement with other recent research about changes in the arctic.

Wildfires play an important role in the global warming and climate change systems, as they not only emit BC but also CO₂ and CH₄. A study by Kelly et al.⁸ in 2013 confirms that forest fires are burning at an unprecedented rate, caused by increasingly warm and dry climate conditions. The authors also note that the current climate change projections let them expect even more wildfire activity in the future. This is in line with the IPCC's expectation that for every 1°C rise in temperature, there will be a doubling in wildfire activity⁹. In addition, the loss of canopy will result in more sunlight reaching the ground, warming it up and thus CO₂ and CH₄ emissions from soil decomposition and thawing of underlying permafrost (in the Arctic). Overall, a vicious circle in terms of global warming and climate change.

An earlier study by Turetsky et al.¹⁰ in 2011 found that Alaskan fires are burning deeper and deeper into the ground, releasing high amounts of GHG's, which have been previously stored in the soil for a long time. Thus, the soils in black spruce stands have shifted from being a net sink of carbon from the atmosphere to becoming a net source.

⁷ Calculation by Jason Box with NASA data.

⁸ Kelly, R et al. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. PNAS, Vol. 110, No. 32, 13055-13060, 2013. doi: 10.1073/pnas.1305069110

⁹ www.ipcc.ch, <http://www.climatecentral.org/news/nw-fires-weather-climate-change-boreal-forests-17778>

¹⁰ Turetsky, MR et al. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience, Vol. 4, 27-31, 2011. doi:10.1038/ngeo1027



Another area where a large number of uncontrolled fires are burning are Canada's Northwest Territories. In 2014, more than 3.3 million ha burned down (i.e. approximately six times the 25-year average), including the Birch Creek Complex, which might now be the largest wildfire in modern Canadian history¹¹. Those fires, and similar ones in other parts of the world, can cause smoke plumes that spread thousands of miles, finally reaching glaciers in, e.g., Greenland (see Fig. 5) and depositing BC there.

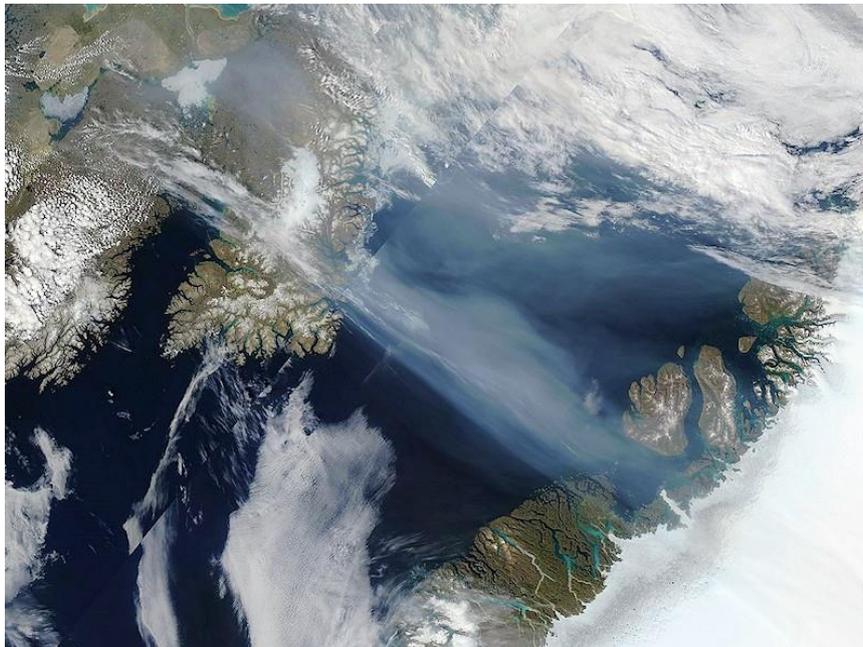


Fig. 5 Smoke plume over Greenland¹²

Complex feedback-loops seem to exist between global warming, wildfire activity and emission of certain GHG's, such as BC, CO₂, CH₄, and other aerosols. There is a clear need for better scientific understanding of these complex atmospheric processes and couplings. Also, the attribution of atmospheric warming to the different sources, like BC, dust and other aerosols, still contains uncertainties.

This is thought-provoking with regards to the envisioned large-scale use of biomass combustion and biofuels. What is the relation of beneficial effects of zero or negative CO₂ emissions from biomass technologies compared to adverse effects, such as the emission of BC, likely contributing to enhanced meltdown of glaciers? It will be important to apply these technologies primarily to modern power and industrial plants that have the necessary closed-systems with emissions control equipment in place (e.g. fabric filters, electrostatic precipitators). Addressing emissions along the whole biomass supply chain will be equally essential. Fig. 6 compares the life cycle PM emissions from dedicated coal firing with biomass co-firing. As you can see, PM emissions are higher for biomass systems, mainly due to the grinding and drying of the biomass (RMA part in Fig. 6), which is required for effective combustion in a conventional boiler and causes significant PM emissions.

¹¹ <http://www.cifc.ca/firewire/current.php> and <http://www.motherjones.com/environment/2014/07/canada-wildfires-climate-change-feedbacks>

¹² Image by NASA MODIS, found on <http://darksnow.org/>



Figure 4-10: PM Emissions from Coal and Biomass Power Systems

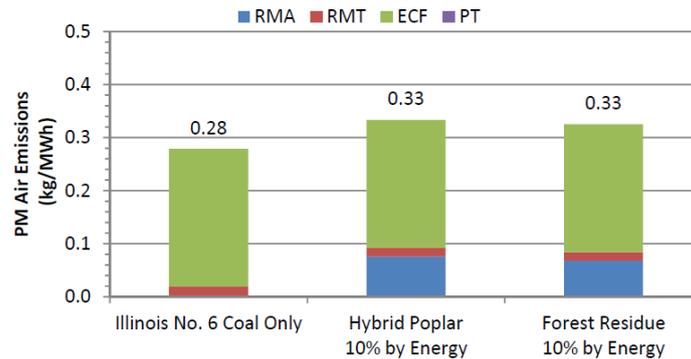


Fig. 6 Life cycle PM emissions from coal and biomass power systems¹³ (RMA = raw materials acquisition, RMT = raw materials transport, ECF = energy conversion facility, PT = product transport)

Apart from this: should we only worry about the global warming effects of BC, whether they will be net warming or cooling? What about the impact of BC/PM on public health? According to Jacobsen¹⁴, open biomass burning (BB) might cause around 250,000 premature deaths per year, with >90% attributable to particulate emissions.

The good news: as the lifetime of BC in the atmosphere is relatively short, and even shorter than previously thought, it will respond quickly to reduction efforts.

Mitigation technologies for BC exist but have to be broadly implemented and incentivised. For example, the mitigation of PM from diesel engines, a large source of BC, appears to be a good starting point. Diesel particulate filters (DPF) could trap more than 90% of PM emissions from vehicles in combination with the use of ultra-low sulphur diesel (ULSD). (I'm actually wishing for compulsory DPF retrofits every time I'm stuck behind an old diesel bus or truck on my bike, sneezing and coughing. Maybe I should get equipment as indicated in Fig. 7.) In my opinion, there is clearly a need for more and faster action, especially if you consider that e.g. in Germany currently only 25% of all cars comply with Euro 5¹⁵.



Fig. 7 Should we be worried about air pollution?¹⁶

¹³ DOE/NETL. Role of alternative energy sources: pulverized coal and biomass co-firing technology assessment. DOE/NETL-2012/1537. August 2012.

¹⁴ Jacobsen, MZ. Effect of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects. Journal of Geophysical Research: Atmospheres, Vol. 119, 8980-9002, 2014. doi:10.1002/2014JD021861.

¹⁵ Kraftfahrt-Bundesamt (German Federal Office for Motor Vehicles) http://www.kba.de/DE/Presse/Pressemitteilungen/2014/Fahrzeugbestand/pm10_fz_bestand_pm_komplett.html?nn=716826

¹⁶ Photos from http://mikesbogotablog.blogspot.co.uk/2013_01_01_archive.html (left) and <http://www.bbc.co.uk/news/uk-scotland-26595625> (right)



Other options for BC/PM mitigation include electric cars, hybrids, H₂ fuel cells, compressed natural gas (CNG), biodiesel, or other forms of transport, like cycling. As an oxygenated fuel, biodiesel contains less carbon but more hydrogen and oxygen than fossil-based diesel. This improves combustion efficiency and reduces PM emissions from unburnt carbon. Although the use of biodiesel cannot completely eliminate BC and other PM emissions, a study just published by MNTRC¹⁷ (Mineta National Transit Research Consortium) indicates a reduction of 17% when using a B20 blend compared to standard ULSD, however, at the cost of higher NO_x emissions (no reduction ever seems to come for free). Through facilitating the deployment and use of clean cookstoves in the developing world, The Global Alliance for Clean Cookstoves¹⁸ aims at equipping 100 million households until 2020 with safe and affordable stoves, thus reducing premature death, GHGs and pollutant emissions.

Short resume:

Due to the complexity of the issue, there is currently no consensus in the scientific literature about the amount of global warming caused by BC-rich emission sources. Further research is necessary to address the related uncertainties. However, as there is agreement on the negative health implications of PM and BC emissions, we do not have to sit and wait until the global warming effects are clarified. We should rather use any option available to us for making the air we breathe cleaner.

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31/10/2014

¹⁷ Kumar, A et al. Combustion chemistry of biodiesel for use in urban transport buses: experiment and modelling. MNTRC report 12-17, October 2014. <http://transweb.sjsu.edu/project/1146.html>

¹⁸ <http://www.cleancookstoves.org/the-alliance/>