The climate impacts of current black carbon and organic carbon emissions

Part 1: The current status of the research field

8 December 2017

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Title: Climate impacts of black carbon and organic carbon

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Funded by: Ministry of Climate and Environment

Project: Climate impacts of black carbon and organic carbon

Project Manager: Bjørn H. Samset

Quality Manager:

Keywords: black carbon, organic carbon, brown carbon, aerosols, emissions, atmospheric lifetime, absorption, radiative forcing, temperature, precipitation, clouds, emission metric, direct effect, indirect effect, semi-direct effect, mass absorption cross-section, coating enhancement, efficacy, Arctic

Abstract: We present a summary of recent research into the climate impact of black and organic carbon. There have been many developments on the research front in recent years, and this rapid pace is expected to continue. The strength of the climate impacts of black and organic carbon is governed by the amount of emissions, how long the aerosols remain suspended in the air after emission, and how effective their various climate interactions are. Current estimates of annual emissions of both black and organic carbon are higher than they were a few years ago. Black carbon is currently estimated to have only a moderate global warming effect, but may have a stronger influence on regional temperatures and precipitation. Organic carbon emissions are still estimated to have a moderately cooling effect.

Language: English

Contents

1 Abstract

We present a summary of recent research into the climate impact of black and organic carbon. There have been many developments on the research front in recent years, and this rapid pace is expected to continue.

Black carbon consists of dark-colored aerosols that absorb radiation and are suspended in the atmosphere or deposited on snow. Organic carbon consists of bright-colored aerosols that mostly reflect radiation in the atmosphere. These aerosols cause various indirect effects which also influence the climate.

The strength of the climate impacts of black and organic carbon is governed by the amount of emissions, how long the aerosols remain suspended in the air after emission, and how effective their various climate interactions are.

Estimates of *emissions* of both black and organic carbon have been adjusted upwards in recent years. Moreover, emissions are currently increasing year by year.

In current climate models the *atmospheric lifetime* of black carbon is estimated at between five and ten days, but more recent research suggests that it may be at the lower end of this range and possibly even as low as three to four days. Higher emissions and shorter atmospheric lifetimes produce model results that are more consistent with observations.

Since black carbon abosrbs solar radition, emissions lead to a warming of the climate system. At the same time, the aerosols warm the surrounding air, which in turn affects clouds. This leads to compensatory cooling. This process, known as the *semi-direct effect*, has long been poorly quantified, but recent studies show that it reduces the overall climate impact of black carbon.

Although the underlying processes are now better understood, the total climate impact of todays black carbon emissions is still uncertain. Recent studies have quantified the effective radiative forcing of anthropogenc black carbon to be 0.08 ± 0.07 Wm^{-2} for a growth in emissions equivalent to 1850–2000. This estimate takes into account the semi-direct effect and second aerosol indirect effects. The global mean warming attributable to current, anthropogenic black carbon emissions was estimated as 0.1 °C.

Parts of the organic carbon emissions are so-called brown carbon, which is absorbent but not to the same extent as black carbon. The level of knowledge about the climate impacts of brown carbon is low.

Organic carbon emissions may also lead to changes in the properties of clouds. Few studies have been conducted that measure the scope of the indirect effects on organic carbon specifically, but recent studies suggest that it is somewhat smaller than previously believed.

Very few studies have examined the temperature impact of organic carbon. One recent study estimated that anthropogenic organic carbon emissions currently cause an average cooling of 0.1 °C.

Emissions of black carbon and organic carbon also affect precipitation. With respect to current emissions, recent studies estimate that the changes in precipitation are marginal from a global perspective, but that they may have significance in some areas.

The climate impacts of both black carbon and organic carbon are dependent on *where* and *when* emissions occur. Multi-model studies show large variations in the radiative forcing caused by emissions from different regions, but the models are often consistent regarding which emission regions the climate is most sensitive to. The direct radiative forcing is strongest in summer, because that is when we have more sunlight. Single-model studies show that cooling from the semi-direct effect of black carbon is strongest in summer, while warming from black carbon deposited on snow and ice is strongest in winter. The warming effect of black carbon is considerably stronger in the Arctic than globally.

Much recent research is based on large-scale international projects, which offer possibilities such as conducting multi-model studies. In addition, several measurement campaigns are being conducted from aircraft and ships that provide increasingly refined information about black and organic carbon, and the information provided by satellites is increasingly detailed.

2 Introduction

The Ministry of Climate and Environment has asked the Center for International Climate Research (CICERO) to compile an overview of the climate impacts of black carbon and organic carbon. The assignment description states:

"Timely reduction of short-lived climate polluters will contribute to slowing down the warming rate, something that is important for achieving the sustainability goals set for 2030 and the long-term goals of the Paris Agreement. However, there is uncertainty regarding the climate impacts of black carbon (BC) and organic carbon (OC). At the same time, there have been many developments on the research front in recent years. There is a wish for updated knowledge about the climate impacts of BC and OC, and about what types of measures are most effective from a climate perspective."

To address these issues, the Ministry of Climate and Environment has requested a report containing:

- An overview (with references) of the status of research on the climate impacts of black carbon, including geographical differences.
- An overview (with references) of the status of research on the climate impacts of organic carbon.

CICERO has previously written about the climate impacts of black and organic carbon on commission from the Norwegian Environment Agency, including a report that calculated the climate impact of emissions from different parts of Norway (Hodnebrog et al., 2013) and a brief report on knowledge level (Aamaas et al., 2015). Knowledge has developed significantly since these reports were written.

First, we define and explain the key processes and effects. Next, we present an overview of new knowledge about black carbon and knowledge about organic carbon. We focus on those areas with the highest level of research activity, and therefore do not write in detail about everything that is relevant for understanding the climate impacts of black carbon and organic carbon. Finally, we summarize and discuss future knowledge development. A further assessment of the status of this research, including the overall climate impact of black and organic carbon, will be prepared in spring 2018.

3 Definitions

This report covers processes and effects as briefly explained below.

Particles or aerosols:

- Organic carbon: Small, bright-colored carbon aerosols that are emitted from, for example, forest fires. The aerosols reflect solar radiation.
- Black carbon: Small, dark-colored carbon aerosols that are emitted from, for example, diesel vehicles and wood burning. The aerosols absorb solar radiation.
- Brown carbon: Organic carbon which, like black carbon, absorbs solar radiation, but only in parts of the solar spectrum.

Possible climate impacts of aerosols:

- Direct effect/direct aerosol effect: When incoming solar radiation encounters an aerosol, the radiation is scattered or absorbed. Absorption leads to warming, scattering to cooling.
- Albedo effect: Aerosols will be deposited on surfaces, including snow and ice. Black carbon aerosols will turn white snow and ice surfaces gray. More incoming solar radiation is absorbed by gray surfaces, and the albedo is reduced. This leads to warming.
- First aerosol indirect effect (also known as the cloud albedo effect): In a cloud with added aerosols, the more numerous aerosols will compete for the same amount of water. It will lead to more, though smaller, cloud droplets. A cloud with many small droplets is brighter than a cloud with a few large droplets. In other words, the cloud will scatter more incoming solar radiation and have a cooling effect.
- Second aerosol indirect effect: In a cloud with more small droplets, as described above, the precipitation processes may be influenced and in turn affect the cloud cover and cloud liquid water content.
- Semi-direct effect: Dark aerosols such as black carbon will absorb incoming solar radiation and thereby warm the surrounding air. This will change the atmospheric stability and may lead to changes in the clouds. This generally leads to cooling. Bright-colored aerosols such as organic carbon cause changes to atmospheric stability to a far lesser degree, so the effect of these aerosols is minimal.

Terms used for processes:

- Mass absorption cross-section (MAC): The ability of black carbon to absorb sunlight is often expressed using this value.
- Coating enhancement: When a black carbon aerosol ages and grows in the atmosphere, it mixes with other liquids and aerosols. As a rule, the aerosol consequently becomes more effective at absorbing sunlight. Coating enhancement quantifies this change.
- Atmospheric lifetime: The average length of time aerosols of black carbon and organic carbon remain suspended in the atmosphere, from the time the aerosols are emitted to the time they are removed from the atmosphere. The aerosols can be either washed out by precipitation processes or deposited directly on the ground. Research shows that the

atmospheric lifetime for these aerosols is approximately one week, for black carbon down towards three to four days.

- Efficacy: The temperature increase a unit of radiative forcing creates relative to the temperature increase for a corresponding unit of radiative forcing from CO_2. Values below 1 indicate weaker warming than for CO_2, values above 1 indicate stronger warming per unit of radiative forcing.

Other terms:

- Teragram (Tg): One thousand billion grams. The standard unit of measurement for global annual emissions of aerosols such as black and organic carbon.
- Emission metric: The impact that emissions of a given component have on temperature or other climate parameters per unit mass emitted, in a given time horizont. In normalized form this provides a metric for the climate impact relative to the climate impact of equivalent emissions of CO_2. The most widely used measure is the global warming potential with a time horizon of 100 years.

Different relevant working groups:

- Coupled Model Intercomparison Project (CMIP): A working group that compares results from different climate models (general circulation models) to systematically examine and improve models. CMIP5 was undertaken prior to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2013), while CMIP6 will be undertaken prior to the sixth assessment report, which is due in 2021.
- Precipitation Driver Response Model Intercomparison Project (PDRMIP): A working group that compares results from different climate models in order to enhance knowledge about changes in precipitation, energy budgets and extreme precipitation events.
- Aerosol Comparisons between Observations and Model (AIROCOM): A working group that compares different observations and results from many models for particles or aerosols. The work is conducted in order to better understand aerosols and how they affect the climate globally. AEROCOM1 was undertaken prior to the IPCC Third Assessment Report (2007), while AEROCOM2 was part of the IPCC Fourth Assessment Report (2013).
- Hemispheric Transport of Air Pollution (HTAP): An international cooperative initiative established to enhance understanding of intercontinental transport of air pollution.

4 The status of black carbon

The term “black carbon” is still used differently in the literature, but most of the more recent studies define it as “an ideally light-absorbing substance composed of carbon” (Petzold et al., 2013) and “carbonaceous material with a deep black appearance” (Moosmüller et al., 2009); that is, a light-absorbing and extremely dark-colored matter composed of carbon. One of the challenges for black carbon is that the simulated distributions of black carbon in the climate models show systematic biases compared to observations in both horizontal and vertical dimensions. We will now review some of the factors that may explain this.

4.1 Emissions

Global black carbon emissions are difficult to quantify exactly, and existing emission figures are therefore uncertain. Because several properties of black carbon are also uncertain, such as lifetime, it is difficult to reduce this uncertainty. In recent years the estimates for global emissions have increased (see Figure 1). In CMIP5 (Lamarque et al., 2010) emissions in year 2000 were estimated at 5.0 Tg while in CMIP6 (Hoesly et al., 2017) they are estimated at 5.8 Tg. The growth in emissions after 2000 is also greater than previously believed, where Hoesly et al. (2017) estimate emissions at 8.0 Tg in 2014. Wang et al. (2016) show that overall uncertainty regarding the scope of the climate impacts of black carbon can be reduced by using geographically high-resolution emissions data.

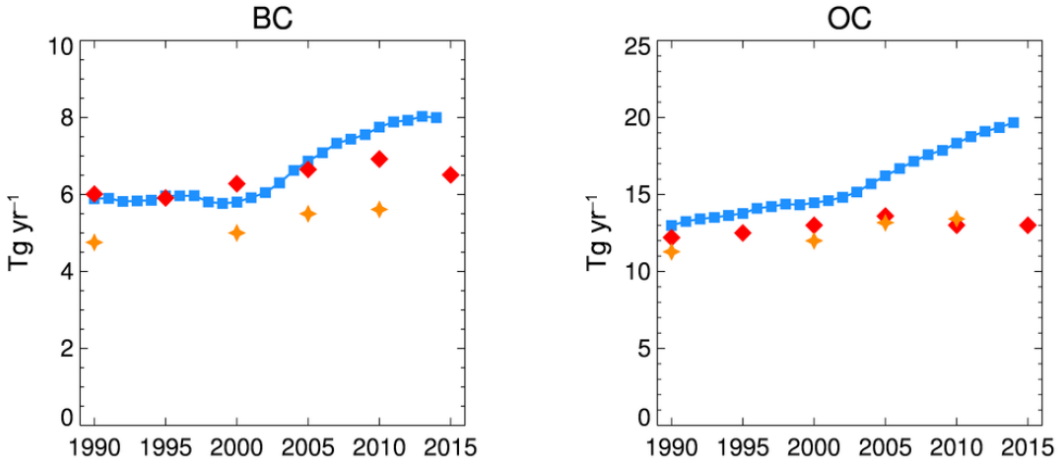

Figure 1: Global emissions of black carbon and organic carbon, 1990–2015 (Myhre et al., 2017a). The yellow symbols represent the emission estimates presented in CMIP5 (Lamarque et al., 2010), and the blue symbols represent the most recent estimates in CMIP6 (Hoesly et al., 2017). The emissions of both black and organic carbon have been adjusted upwards. Several emission estimates, denoted by red dots, are from the ECLIPSE project (Klimont et al., 2016), which was conducted in the period between CMIP5 and CMIP6.

4.2 Process understanding

4.2.1 Atmospheric lifetime

The climate impacts of black carbon are governed by, among other things, the atmospheric lifetime. The aerosols can either be washed out by precipitation processes or deposited directly on the

ground, but the climate models differ significantly as to how effective this wet removal process is (Mahmood et al., 2016). The longer the atmospheric lifetime, the stronger the direct effect of black carbon. Longer atmospheric lifetime means that the aerosols remain longer in the atmosphere and therefore affect the atmosphere over longer time. In addition, the aerosols could be transported further and higher. The vertical distribution of black carbon in the atmosphere has not yet been established. (Samset et al., 2014;Schwarz et al., 2013;Wang et al., 2014a). Black carbon is more effective at absorbing radiation at high altitudes in the atmosphere than aerosols located at lower altitudes (Zarzycki and Bond, 2010). The reason for this is that at high altitudes, aerosols will absorb not only incoming solar radiation but also solar radiation reflected from lower-level water vapor, aerosols and clouds. This reflected solar radiation would otherwise have disappeared right back into space. Nonetheless, the temperature at ground level could be reduced when the aerosols absorb radiation at high altitudes (Ban-Weiss et al., 2012;Lund et al., 2014).

In current climate models the atmospheric lifetime of black carbon is estimated at somewhere between five and ten days, but there is reason to believe that these models overestimate the atmospheric lifetime of black carbon. Wang et al. (2014a) find extremely low concentrations of black carbon in airborne measurements taken over the Pacific Ocean, which indicates that wet deposition is far more effective than that which is normally implemented in models. The HIAPER Pole-to-Pole Observations (HIPPO) (Schwarz et al., 2013) airborne field campaign has made this progress possible by taking measurements of vertical profiles of black carbon in the Pacific Ocean over five years. Because there are very few local sources of black carbon in the Pacific, most of what is measured there is expected to have been transported there. The Pacific is therefore a good area for testing climate models. Several research groups have examined what these results mean for the atmospheric lifetimes of black carbon. Wang et al. (2014b) adjust the mean global lifetime downwards from 7.3 days to 4.4 days in AEROCOM1. Samset et al. (2014) compared the aircraft observations with data from 13 AEROCOM2 climate models and found that the lifetime in the models had to be adjusted downwards from a model average of 6.8 days to less than five days in order to reproduce the concentrations of black carbon over remote sea areas. A lifetime for black carbon of three–four days provided the best match with the observations. Longer lifetimes resulted in overestimated concentrations in these areas. This downward adjustment led to a 25 percent reduction in the model median's direct radiative forcing since pre-industrial times.

4.2.2 Absorption capacity

Black carbon aerosols absorb sunlight in the atmosphere, but the research literature disagrees on how strongly. Black carbon is never found as pure carbon matter in the atmosphere (Petzold et al., 2013), so the optical properties of black carbon depend heavily on how long the aerosol has been in the atmosphere and on atmospheric conditions, including relative humidity and the presence of other substances to clump together with black carbon. The ability of black carbon to absorb sunlight is expressed by the mass absorption cross-section. Observational and model studies produce different values for the mass absorption cross-section. A review of the scientific literature in 2006 (Bond and Bergstrom, 2006) concluded by recommending a value of 7.5 $m^2\ g^{-1}$ at a wavelength of 550 nm for freshly formed aerosols of black carbon. They find a range from 5 $m^2\ g^{-1}$ for combustion and pure aerosols to 11 $m^2\ g^{-1}$ for aged aerosols that are coated with other matter. This range tallies with more recent observations, although different measurement techniques and measurements of different air masses produce very different values. For example, Cui et al. (2016) found mass absorption cross-section values of around 10 $m^2\ g^{-1}$ at a wavelength of 678 nm for air from rural northern China while Ram and Sarin (2009) observed a range of between 6 and 14 $m^2\ g^{-1}$ at a wavelength of 678 nm at different sites in India and Yttri et al. (2014) measured values of around 6 $m^2\ g^{-1}$ at a wavelength of 522 nm in the Arctic. Zanatta et al. (2016) found a representative mass absorption cross-section value of 10 $m^2\ g^{-1}$ at a wavelength of 637 nm based on observations from nine different background measurement sites spread throughout Europe. Previous research has show a broader range of values, geographical and seasonal, than those in this study, and Zanatta et al. (2016) indicates an uncertainty of ±30-70% due to a lack of appropriate reference methods. The 10 climate models used in Stjern et al. (2017) (through cooperation in PDRMIP) has a spread in

globally averaged mass absorption cross-section value from 3.3 to 9.9 $m^2 g^{-1}$ at a wavelength of 550 nm, with an average of 6.0 $m^2 g^{-1}$. The recommendation of Bond and Bergstrom (2006) remains valid.

The mass absorption cross-section is governed by, inter alia, how black carbon aerosols mix with other aerosols in the atmosphere after being emitted. The black carbon aerosols are often coated with other materials which change the aerosol's optical properties, usually by making the aerosols more effective at absorbing sunlight (Bond and Bergstrom, 2006). The way in which each aerosol ages in the atmosphere is governed by complicated conditions. The additional material does not necessarily have to be absorptive in itself, but causes the black carbon to become even more absorptive. The result is that the mass absorption cross-section value increases. Absorption enhancement is a factor that indicates the extent of this enhancement since the aerosol was new in the atmosphere. The findings in Bond and Bergstrom (2006) are widely used, including the recommended absorption enhancement factor of 1.5 for use in climate models. It was based on currently valid observations and theory. Laboratory studies (Cappa et al., 2012;Lack et al., 2009;Zhang et al., 2008) find similar values, but newer studies diverge considerably, from 1.0 to 3.0. Some differences can be explained by the use different instruments and methods (f.eks. Pokhrel et al., 2017), variations in how much black carbon was internally mixed (f.eks. Schwarz et al., 2008) and differences in emission sources of black carbon (f.eks. Nakayama et al., 2014). But the key factor is likely the vast differences in what is deemed standard; this is, what is a newly emitted aerosol and what is an aged aerosol. Different studies measure different factors, and will therefore cite different factors. The research literature can therefore cause confusion, with studies that cite apparently different enhancement factors often agreeing on the total amount of absorption that comes from black carbon. One finds low values of absorption enhancement in studies that compare air samples dominated by fresh, local sources compared with de-coated and pure aerosols of black carbon (f.eks. Cappa et al., 2012;Lan et al., 2013), while high values are found when pure aerosols of black carbon are compared with fully aged aerosols, (f.eks. Cui et al., 2016;Peng et al., 2016). Peng et al. (2016) examined urban, polluted air from Beijing and Houston in a chamber. They could therefore closely examine how black carbon ages. They found an absorption enhancement factor of 2.4. Cui et al. (2016) developed a different method, whereby aerosols were collected in northern China and de-coated until they were left with pure black carbon. Measurements were taken of the mass absorption cross-section at different stages. This study found an average absorption enhancement factor of 2.3. The findings in Peng et al. (2016);Cui et al. (2016) are actually consistent with Bond and Bergstrom (2006). The 1.5 factor in Bond and Bergstrom (2006) applies to the transition from newly formed aerosol to aged aerosol. Going a step further and including changes in the optical properties from clean aerosol particle to freshly formed aerosol particle, results in an additional factor of 1.5. In other words, the total factor from clean aerosol particle to aged aerosol particle is 2.3 according to Bond and Bergstrom (2006), which is consistent with more recent research. The correct value for the absorption enhancement factor is a subject of debate in the literature (f.eks. Boucher et al., 2016). It is important to keep in mind that it is not the absorption enhancement factor that is most critical to quantifying the climate impact of black carbon, but rather the absorption enhancement factor. We conclude that the recommendation of Bond and Bergstrom (2006) remains valid.

4.2.3 Semi-direct effect

Black carbon exhibits extremely strong absorption of solar radiation wherever aerosols are present in the atmosphere. This leads to significant local warming, which in turn causes changes in the temperature profile in the atmosphere and atmospheric stability. Depending on where in the atmosphere this warming takes place, it can lead to significant changes in cloud cover (e.g., Koch and Del Genio, 2010). For example, clouds may evaporate if the aerosol-induced warming occurs inside the clouds. Black carbon below the cloud cover may enhance convection and strengthen the cloud layer. If the aerosols are located above the clouds, they will stabilize the underlying air layer and thereby strengthen certain types of clouds (stratocumulus) and weaken others (cumulus).

The semi-direct effect of aerosols has long been poorly quantified. However, recent studies show that overall it is negative and that is counteracts and reduces the overall climate impacts of black carbon. The studies from Hodnebrog et al. (2014);Samset and Myhre (2015) are both single-model studies, but the trend is clear. Stjern et al. (2017) make similar findings based on results from five climate models. The latter study shows that a tenfold increase in black carbon will lead to an instantaneous radiative forcing of 2.10 Wm^{-2}, while the corresponding figure for the semi-direct effect is -0.64 Wm^{-2}. Stjern et al. (2017) also modeled an increase in low-level clouds due to increased emission but a reduction in middle-and high-level clouds. The estimates for the present-day semi-direct effect of black carbon varies between the models that have attempted to quantify it, and regionally it will also vary greatly from year to year because it depends on the distribution of clouds. Variations are also due to choice of method, where Zelinka et al. (2014) showed that 20 percent of the difference between the various models is attributed to differences in the cloud fields used. In other words, there is considerable scientific uncertainty, but it is clear that calculations of the climate impacts of black carbon ought to include the semi-direct effect. Several studies do not quantify the semi-direct effect alone, but automatically include it in their climate models. (Baker et al., 2015;Stohl et al., 2015;Stjern et al., 2017). These climate models have shown a relatively low temperature response from black carbon at ground level, which may indicate a marked cooling from the semi-direct effect.

4.3 Effects on temperature and precipitation

Although we have a better understanding of the underlying processes, the uncertainty about the climate impacts of black carbon remains (Stjern et al., 2017), see, inter alia, Figure 2. Recent studies show that black carbon is among the components that create the greatest variation in the models' climate response (Myhre et al., 2017b;Samset et al., 2016). The likely reason is that modeling of the processes associated with absorption in the atmosphere is poorer than other radiative forcing. In most cases, it is local emissions that govern the radiative forcing from the direct effect in a region, but Stjern et al. (2016) showed that emission reductions of black carbon in Asia may also significantly influence Europe and North America. IPCC (Boucher et al., 2013) estimated radiative forcing from the direct effect of black carbon from the combustion of fossil fuels and biofuels at 0.4 Wm^{-2}, with an uncertainty range of (0.05-0.8 Wm^{-2}), based on Myhre et al. (2013);Bond et al. (2013). In addition, black carbon emissions create several other effects. Recently Stjern et al. (2017) quantified the effective radiative forcing, including the semi-direct effect and other indirect effects, at 0.09 Wm^{-2} for emission growth equivalent to 1850–2000 based on nine climate models. Additional effects include warming from black carbon that is deposited on snow, which reduces the albedo of snow and ice surfaces. IPCC (Boucher et al., 2013) estimates this effect to have a radiative forcing of 0.04 Wm^{-2}, with an uncertainty range of 0.02-0.09 Wm^{-2}. In other words, this effect is relatively small in global terms but it is two to four times more effective per unit than radiative forcing from CO_2 at raising the temperature (Boucher et al., 2013).

Relatively few studies have examined the climate impacts of black carbon alone. Because the semi-direct effect reduces warming and the efficacy of black carbon is lower than that of CO_2 (with the exception of the snow albedo effect), the change in global temperature resulting from anthropogenic black carbon emissions is negligible. Stjern et al. (2017) finds an efficacy of 0.80, which is 20 percent weaker than for CO_2. This efficacy calculation is based on effective radiative forcing. Previous studies which only quantified the instantaneous radiative forcing found even lower efficacy values (Yoshimori and Broccoli, 2008).

Among the studies that examined the global temperature response of black carbon, Mahajan et al. (2013) found a warming of 0.52 °C for a tenfold increase in atmospheric concentration. Jones et al. (2007) modeled a warming of 0.28 °C for an emissions increase from 1860 to 2000. Other studies removed black carbon from their models and consequently found a cooling. Jacobson (2010) removed all fossil black carbon and found a global cooling of between -0.3 and -0.5 °C. Baker et al. (2015) removed all anthropogenic emissions from four climate models and found a mean cooling of -0.044 °C, though with models that showed large variation and some warming (from -0.152 to

+0.0085 °C). The most recent study is Stjern et al. (2017) , which used nine climate models to calculate the climate impacts of a tenfold increase in emissions. They found that present-day global emissions lead to a warming of 0.07 ± 0.05 °C. If they had used the most recent emission estimates, the temperature effect of present-day emissions would be slightly greater.

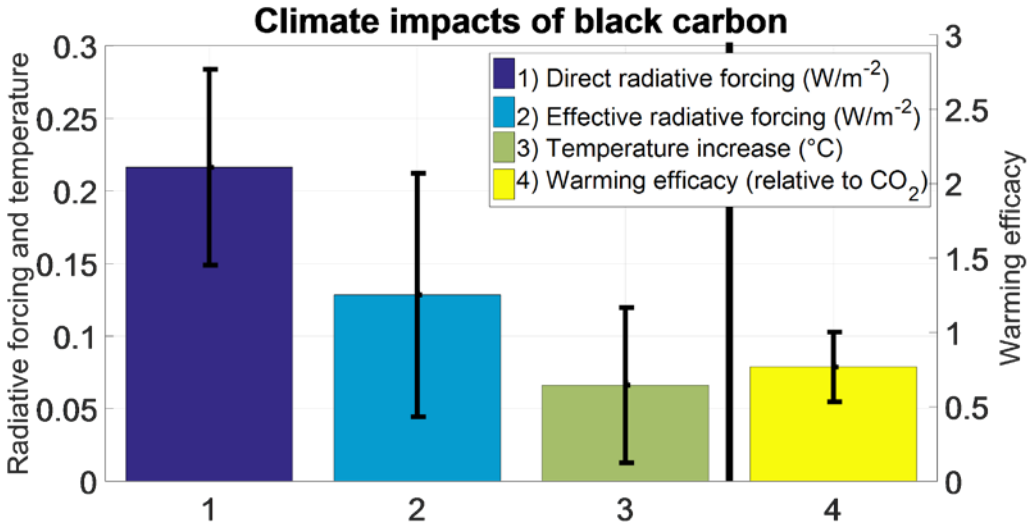

Figure 2: The impact of present-day emissions of black carbon on radiative forcing and temperature (see the left-hand axis) based on five models in Stjern et al. (2017). The efficacy (see the right-hand axis) shows the temperature increase a unit of radiative forcing leads to for black carbon compared with CO2. Values below 1 indicate weaker efficacy than for CO2. The uncertainty shows the standard deviation for the results from these five models.

These changes in atmosphere and temperature also affect precipitation. Myhre et al. (2017b);Samset et al. (2016) found that radiative forcing from black carbon has a negligible impact on global temperature but that this component is among the ones that show the largest reductions in precipitation in spite of temperature increases. The changes in precipitation can be divided into two parts. The fast response comes from absorption by aerosols in the atmosphere, and entails a net reduction in precipitation. The slow response scales with increases in global temperature and causes increased global precipitation. Previous studies have shown that the fast response is the most important factor in explaining the total change in precipitation for black carbon emissions. (Andrews et al., 2010;Kvalevåg et al., 2013;Samset et al., 2016). Samset et al. (2016) used nine climate models and found large differences in precipitation changes between the models. Over ocean regions, they modeled that the fast response dominated, while over land regions the slow response dominated. Stjern et al. (2017) examined the results more closely and found that the convective precipitation component is reduced by the fast response, while this precipitation shows a slight increase over land. When simulating a tenfold increase in black carbon, Stjern et al. (2017) found a reduction in precipitation of -15 ± 9 mm/yr. In other words, the globally averaged changes in precipitation are small. But on a regional scale the effect can be quite large, with, for example, droughts in Southern Europe and Central America and increased precipitation in the region around India.

4.4 Regional differences

The warming effect of black carbon is considerably stronger in the Arctic than globally. Sand et al. (2013a) , which was a single-model study, found that a tenfold increase in black carbon concentrations in the mid-latitudes (28°N–60°N) shows a warming of 1.1 °C in the Arctic (north of 60°N). The warming rate in the Arctic is approximately three times higher than the global rate. The

location of black carbon emissions is highly significant for the impact in the Arctic. Previous studies modeled a cooling at ground level in the Arctic when emissions occur in the Arctic (Shindell and Faluvegi, 2009;Sand et al., 2013a), while more recent studies that included the albedo effect on snow show a strong warming in the Arctic. Sand et al. (2013b) concluded that emissions in the Arctic cause a five-time stronger warming effect in the Arctic compared to emissions at mid-latitudes. Sand et al. (2016) subsequently showed that emissions from Russia and the Nordic countries have the greatest impact on the Arctic per unit mass emitted, but because emissions are far larger in other regions, it is Asia and other large emission regions that contribute most overall to Arctic warming.

The climate impacts of these emissions also show seasonal variations. Bellouin et al. (2016) found that radiative forcing per unit mass emitted is largest in summertime, when there is more sunlight available for absorption. This is partly offset by the fact that the cooling semi-direct effect is also strongest in summertime, while warming from the albedo effect is strongest in wintertime.

Emission location is also significant. Multi-model studies show large variations in the amount of radiative forcing from different regions, but the models often agree as to which emission regions are most and least sensitive. Yu et al. (2013) under HTAP find that emissions from Europe cause the largest radiative forcing per unit mass emitted, while emissions from North America, South Asia and East Asia are quite similar. Bellouin et al. (2016) also finds that emissions in Europe exert stronger radiative forcings per unit mass emitted than in East Asia. As part of HTAP2, Stjern et al. (2016) recently showed that there are small differences in the direct radiative forcing between Europe and East Asia.,The Middle East exert the largest forcings per unit emitted, while South Asia takes second place and Russia third. North America has the lower radiative forcing per unit emitted. The reason the Middle East is the most emissions-sensitive area is likely its desert areas with high albedo, which form a stark contrast to the dark-colored aerosols of black carbon. A similar effect is found for emissions in areas close to the snow- and ice-covered Arctic.

4.5 Emission metrics

The climate impacts of different types of emissions can be compared using emission metrics. The two most common emission metrics are global warming potential (GWP, cumulative radiative forcing) (IPCC, 1990) and global temperature change potential (GTP) (Shine et al., 2005). By normalizing to CO_2, a comparison can be made with the climate impacts of emissions of a unit of CO_2. Studies of emission metrics are often based on previous studies of radiative forcing; for example Collins et al. (2013) calculated emission metrics based on Yu et al. (2013) and Aamaas et al. (2016) on Bellouin et al. (2016). Aamaas et al. (2016) was the first study to calculate emission metrics for emissions in summertime and wintertime. The same trends for radiative forcing discussed above are also found for the emission metrics.

The absolute form of GTP, called AGTP, is like a very basic climate model. These can be used to calculate global temperature changes in a range of emission scenarios (e.g., Aamaas et al., 2016). Ideally, far more advanced earth system models ought to be used to estimate temperature changes, but emission metrics are very useful, easy to use, flexible and transparent.

In recent years, emission metrics have been used to calculate regional temperature changes. Regional temperature change potential (RTP) (Shindell and Faluvegi, 2010) calculates temperature changes in four latitude bands (90 °S- 28 °S, 28 °S - 28 °N, 28 °N – 60 °N, 60 °N – 90 °N). Collins et al. (2013) used this concept to calculate absolute RTP values for black carbon emissions from different regions. Similarly, Aamaas et al. (2017) calculated ARTP values for the same dataset as Aamaas et al. (2016) did for AGTP values. The difference is that the ARTP concept illustrates regional differences in efficacy in far more detail than does AGTP. Global temperature changes can also be calculated based on a weighted mean of ARTP values. Aamaas et al. (2017) argues that this provides a better estimate of global temperature. One of the main findings in Aamaas et al. (2017) is

that black carbon emitted close to the snow- and ice-covered Arctic, and during wintertime, is given greater weighting with ARTP than with AGTP. This is because the albedo effect is given greater weight. Another key finding is that the temperature effect in the Arctic is far greater than the global effect for black carbon, and to a greater extent than for other emission components. The Arctic temperature response is 390 percent and 240 percent larger than the global response for winter emissions in Europe and East Asia respectively. The study also shows that black carbon dominates, especially for European emissions, in terms of the Arctic temperature response compared with other short-lived climate forcers based on current emissions (emissions in 2008) during wintertime, yet globally gives the same temperature response as several other short-lived climate forcers.

It must be mentioned that the parameters behind the ARTP concept are largely based on a model only, so more studies are needed that can introduce significant changes in the estimates. Moreover, existing ARTP values have not yet taken into account the latest knowledge about the short lifetime and semi-direct effects of black carbon, and are therefore unable to provide any high estimates of the climate impacts of emission changes.

5 The current status of organic carbon

5.1 Emissions

As for black carbon, estimates for organic carbon emissions have been adjusted upwards (see Figure 1). In CMIP5 global emissions for 2000 were estimated at 12.6 Tg (Lamarque et al., 2010), while in CMIP6 they were estimated at 14.4 Tg (Hoesly et al., 2017). The emissions have also increased since 2000, and are estimated at 19.6 Tg by Hoesly et al. (2017) in 2014.

5.2 Process understanding

5.2.1 Brown carbon

Some of the organic matter is brown carbon, which is absorbent but not to the same extent as black carbon. Absorption occurs largely on the short wavelengths (Lu et al., 2015). Brown carbon is emitted directly through combustion, but is also produced in the atmosphere from secondary sources. Secondary organic carbon can lead to the production of brown carbon, from combustion, as in biomass combustion and from biofuels (Zhang et al., 2013;Saleh et al., 2013), and from biogenic organic matter (Liu et al., 2016;Zhang et al., 2013). The level of knowledge about the climate impacts of brown carbon is low, and the uncertainties are large. Liu et al. (2014) find that as much as 20 percent of direct absorption into the atmosphere is attributed to brown carbon. Zhang et al. (2017) also found brown carbon in the upper atmosphere after conducting airborne field campaigns over central parts of North America. As for black carbon, the climate impacts of brown carbon will increase with height, so if it is transported higher than estimated by the models, the estimated climate impacts will be undermined.

The radiative forcing of black carbon is governed not only by absorption enhancement, but Saleh et al. (2015) show that the composition of substances that clump together around black carbon determines the strength of radiative forcing from black carbon; that is, how much constitutes reflective aerosols and how much constitutes brown carbon. Both absorption enhancement and the amount of brown carbon strengthen the radiative forcing (Liu et al., 2015). But there are interactions, so that one may overestimate the total effect if the effects of absorption enhancement and brown carbon are calculated separately in models (Saleh et al., 2015).

5.2.2 Indirect effects

Organic carbon emissions not only have direct effects but also lead to interactions between aerosols and clouds, including the first indirect effect. Few studies have examined aerosol components separately, but have instead examined what proportion aerosol–could interactions constitute of all aerosol types combined.

Volcanic eruptions can be regarded as natural experiments to measure the sensitivity of aerosol–could interactions. Violent volcanic eruptions can lead to the formation of sulfate aerosols high in the atmosphere, but less violent eruptions can emit aerosols at lower heights. Malavelle et al. (2017) investigated a volcanic eruption on Iceland in 2014–2015 where emissions occurred at heights of up to 3 km. They found that cloud droplets reduced and led to brighter clouds, the first indirect effect, and that these changes are consistent with previous literature. However, they observed no measurable change in cloud amount or cloud liquid water in the clouds. This may indicate that the other indirect effects are small.

The indirect effects can also be examined by using different sensitivities and compare them with the historical development. Stevens (2015) used a simple model to draw random values along different parameters in order to model realistic estimates of the radiative forcing of aerosols. Based on the rise in global temperature by approximately 0.3 °C from 1850 to 1950, he argues that the total radiative forcing from aerosols cannot be more negative than -1.0 W/m^2. IPCC estimated this radiative forcing at -0.9 W/m^2, though with a wide range (Boucher et al., 2013). More recent studies suggest that the lower limit for the range, that is, the most negative values, needs to be raised.

5.3 Effects on temperature and precipitation

IPCC (Boucher et al., 2013) estimated radiative forcing, including indirect effects, for secondary organic carbon at -0.03 Wm^{-2} with an uncertainty range of -0.27 to -0.02 Wm^{-2} and for primary organic carbon from combustion of fossil fuels and biofuels at -0.05 Wm^{-2} with an uncertainty range of -0.09 to -0.02 Wm^{-2}, based in part on multi-model studies such as Myhre et al. (2013). Combustion of biomass also causes large emissions of organic carbon, but these activities also emit black carbon, so the total radiative forcing for the direct aerosol effect is almost equal to zero (Boucher et al., 2013). Even the direct radiative forcing is associated with large uncertainties; for example, a study based on 10 models found a variation of between -2.4 to -17.9 mWm^{-2} per Tg organic carbon emission (Stjern et al., 2016).

Few studies have calculated temperature and precipitation from organic carbon emissions separately from the other aerosol emissions. Baker et al. (2015) removed all anthropogenic organic carbon emissions in four climate models and found an average warming of 0.13 °C, but where one of these showed a slight cooling. This cooling, however, lay within the model's uncertainty range and may have resulted from internal variability in the model.

Organic carbon also affects precipitation, mainly through the slow surface temperature response. Baker et al. (2015) modeled both an increase and a decrease in global precipitation by removing organic carbon emissions, but the models always agreed that the change in precipitation followed the change i surface temperature. In other words, a cooling caused by organic carbon emission reductions means a decrease in precipitation. In any case, the global changes in precipitation are small, where Baker et al. (2015) finds a mean increase of 3 mm per year when all anthropogenic emissions are removed. This increase occurs mainly in the northern hemisphere, and includes a northward shift in the precipitation zone over the tropics, called the intertropical convergence zone.

5.4 Regional differences

The emission location determines the size of the radiative forcing and climate impacts of the emissions. As for black carbon, different models show large variations, but the models often agree on which emissions locations are most and least sensitive. The results from the nine models in HTAP show that for many emissions the differences in direct radiative forcing per unit mass emitted are quite small but that those for East Asia are smallest (Yu et al., 2013). Emissions in North America and Europe have the largest direct radiative forcing per unit mass emitted. Bellouin et al. (2016) also finds that emissions in Europe exert larger radiative forcings per unit mass emitted than in East Asia. The relative differences are larger in HTAP2. Stjern et al. (2016) found the same pattern as for black carbon, with the strongest direct radiative forcings per unit mass emitted for the Middle East and South Asia. Emissions in Russia show the weakest sensitivity. Furthermore, they confirm the findings of previous studies where the radiative forcing from European emissions per unit mass emitted were larger than those from East Asia. The extent of radiative forcing is influenced by wet deposition conditions. The dry atmospheric conditions over the Middle East mean that emissions will have greater impacts there than in other regions.

As for black carbon, the climate impacts of black carbon also vary according to season. Bellouin et al. (2016) found that the radiative forcing per unit mass emitted is largest during summertime. This is because more sunlight enhances the direct aerosol effect during summertime.

5.5 Emission metrics

The description of the emission metric for black carbon also applies for organic carbon and other emission types. The trends that have already been discussed regarding radiative forcing for organic carbon are also found regarding trends in emission metrics. For black carbon, the significance of deciding whether to base the temperature calculations on AGTP or ARTP can be crucial, while the differences are far smaller for organic carbon. Organic carbon and black carbon can influence the climate system in the same time scales, so the relative strength between these two is equal regardless of time horizon, while these aerosols have greater significance at short time scales (the initial years after being emitted) than for CO_2 or methane emissions.

Conclusion

We have presented recent research on black carbon and organic carbon. A summary is presented on the first two pages.

The climate impacts of these emissions is still the subject of active scientific debate. This will continue to be an active field of research, and we can expect that the knowledge level will also increase rapidly in the coming years. Further scientific assessment of the status of the research will be developed in spring 2018.

One of the challenges for black carbon is that the simulated distributions of black carbon in the climate models show systematic differences from observations in both horizontal and vertical dimensions. Nonetheless, whether these differences are due to wrong lifetimes for black carbon, wrong estimates for emissions, deficient processes represented in the models or a combination of these is a topic of active debate. The actual magnitude of the semi-direct effect will likely continue to be discussed. The processes that cause the semi-direct effect will likely be described in more detail in the research literature.

Analysis of more airborne field campaigns will continue to be important. Over the coming years a series of new airborne measurement campaigns will be conducted, in remote regions such as over the oceans and in the Arctic, and close to emission areas such as India. Comparing these results with forecasts from updated climate models will provide a better understanding both of global black carbon emissions and of their lifetime in the atmosphere.

As new studies with updated calculations of radiative forcing are gradually published, the emission metrics for black carbon and organic carbon can be updated. For example, no emission metrics have been calculated from the results of the HTAP2 multi-model project. Based on this dataset, far more emission regions can be compared than has been done in previous studies, and continents can be divided into emission regions. For example, Europe is often the most relevant region for those interested in the climate impacts caused by emissions from Norway, while it is possible to separate out the Nordic countries in HTAP2, which probably provides a better estimate of the actual global impacts of emissions in Norway.

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