REPORT 2018:08

The climate impacts of current black carbon and organic carbon emissions

CICERO
Center for International
Climate Research

The climate impacts of current black carbon and organic carbon emissions

Part 1: The current status of the research field

Part 2: Assessment and regional perspective

20 June 2018

Borgar Aamaas, Marianne T. Lund, Gunnar Myhre, Bjørn H. Samset, Camilla W. Stjern, Steffen Kallbekken

CICERO Senter for klimaforskning
P.B. 1129 Blindern, 0318 Oslo
Telefon: 22 00 47 00
E-post: post@cicero.oslo.no
Nett: www.cicero.oslo.no

CICERO Center for International Climate Research
P.O. Box 1129 Blindern
N-0318 Oslo, Norway
Phone: +47 22 00 47 00
E-mail: post@cicero.oslo.no
Web: www.cicero.oslo.no

Title: The climate impacts of current black carbon and organic carbon emissions

Authors: Borgar Aamaas, Marianne T. Lund, Gunnar Myhre, Bjørn H. Samset, Camilla W. Stjern, Steffen Kallbekken

Funded by: Ministry of Climate and Environment

Project: Climate impacts of black carbon and organic carbon

Project Manager: Bjørn H. Samset

Quality Manager: Jan S Fuglestvedt

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, emissions, mitigation, temperature, sectors

Abstract: In Part 1, 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 global 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.

In Part 2, we use the conclusions from Part 1 to assess differences between emission regions and sectors in terms of climate impact of BC and OC. We emphasize here that the conclusions in the following pages are based on our assessment guided by recent literature, and as such are not necessary representative of the whole research community. In summary, we find that:

- The climate impacts of aerosols emitted in a given region may be both local and remote. There is no direct connection between the pattern of emission, radiative forcing and temperature change. The sensitivity of global temperature to black carbon emissions also differs by region. Hence, the mitigation potential of BC and OC (in terms of global temperature change) needs to be separately considered for each emission region.
- Presently, East Asia, South Asia and Southern Africa are the main BC emission regions, each causing around 0.01 °C of global warming. The Russia, Belarus, Ukraine and Caucasus region represents a similar amount of warming, but for much lower emissions (25% of those in East Asia), illustrating the regional difference in sensitivity to emissions.
- The residential sector (fuel for cooking and heating) emits the most BC, globally and in the main emissions regions. In East Asia, the energy sector also contributes strongly.
- The mitigation potential of warming BC is strongly dependent on co-emission with cooling OC. Transportation stands out as the sector with lowest co-emissions of OC, suggesting higher mitigation potential in regions where transportation contributes significantly to global BC emissions. North Africa and the Middle East, East Asia and South America are examples.
- BC has likely been a contributor to the recent strong Arctic warming. The sensitivity of Arctic temperature is highest for high latitude source regions, notably Europe and the Russia, Belarus, Ukraine and Caucasus regions. In absolute impact, East Asia and South Asia are the strongest contributors to Arctic warming through BC emissions.
- The climate impact of aerosols extends beyond temperature, to precipitation and extreme weather. However, we find that present knowledge is insufficient to quantify the impacts of present BC and OC emissions on global or regional precipitation patterns. This is an area of very active research, and will likely have progressed when the IPCC 6th Assessment Report is published.

Language: English

Contents

Part 1: The current status of the research field

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 a compensatory cooling effect. 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 today's black carbon emissions is still uncertain. Recent studies have quantified the global effective radiative forcing of anthropogenc black carbon to be 0.08 ± 0.07 Wm^{-2} for a growth in emissions from 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 to 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 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 assessed 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, follows in part 2 of this report.

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, over a given time horizon. In normalized form this provides a weight for the climate impact of a given mass of the component in question per same mass of emissions of CO_2. The most widely used measure is the global warming potential (GWP) 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 research

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 emission estimates. 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.

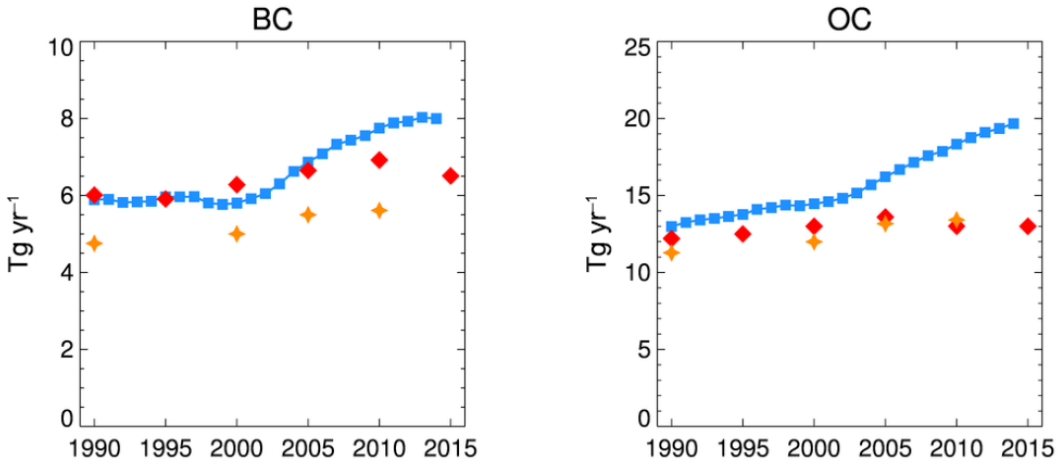

Figure 1: Global emissions of black carbon and organic carbon, 1990–2015 (Myhre et al., 2017a). The yellow symbols represent the emission estimates presented in CMIP5 (Lamarque et al., 2010), and the blue symbols represent the most recent estimates in CMIP6 (Hoesly et al., 2017). The emissions of both 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). Longer atmospheric lifetime means that the aerosols remain in and affect the atmosphere over longer time, which increases the direct effect of black carbon. In addition, this allows the aerosols to be transported further and higher up. (Samset et al., 2014; Schwarz et al., 2013; Wang et al., 2014a) The efficiency with which black carbon absorbs radiation increases with altitude (Zarzycki and Bond, 2010). The reason 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 been emitted to space. In some locations, this atmospheric absorption can be so efficient that the amount of solar radiation reaching the surface is reduced, thereby causing a cooling. (Ban-Weiss et al., 2012; Lund et al., 2014), Mostly, however, increased black carbon concentrations will heat the underlying surface.

Partly due to uncertainties in the lifetime, 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). 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 global 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. (2017b) (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 interactions. 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 mass absorption coefficient. 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 (2015b) are both single-model studies, but the trend is clear. Stjern et al. (2017b) 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. (2017b) 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 must include the semi-direct effect. Recent studies generally do not quantify the semi-direct effect separately, but they do automatically include it in their climate models as rapid adjustments to the increase in black carbon concentrations. (Baker et al., 2015b; Stohl et al., 2015; Stjern et al., 2017b). Compared to indications from previous studies which considered only the direct effects of black carbon, studies will fully coupled 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., 2017b), 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; IPCC AR5) estimated radiative forcing from the direct effect of black carbon from the combustion of fossil fuels and biofuels at 0.4 Wm^{-2} at a global scale, with an uncertainty range of (0.05-0.8 Wm^{-2}), based on Myhre et al. (2013b); Bond et al. (2013). In addition, black carbon emissions create several other effects. Recently Stjern et al. (2017b) 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 the snow albedo 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, it 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.

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. (2017b) finds an efficacy of 0.80, in other words 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. (2015b) 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. (2017b) , 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.

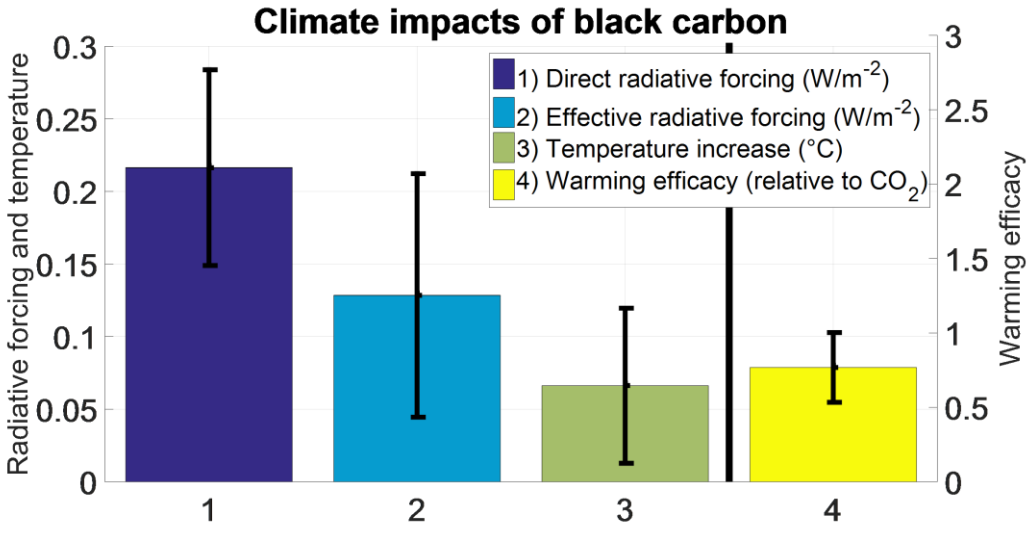

Figure 2: The impact of present-day emissions of black carbon on radiative forcing and temperature (see the left-hand axis) based on five models in Stjern et al. (2017b). The efficacy (see the right-hand axis) shows the temperature increase a unit of radiative forcing leads to for black carbon compared 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 although the radiative forcing from black carbon has a smaller impact on global temperature than other climate drivers, this component is among the ones that show the largest changes in precipitation per degree warming. It also differs from the other climate drivers in that it causes 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. (2017b) 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. (2017b) 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, precipitation reduction 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 (per unit of emitted mass) 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 lowest 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) (IPCC, 1990) and global temperature change potential (GTP) (Shine et al., 2005). The GWP is the ratio of the integrated radiative forcing over a given time horizon for a unit emission of the component in question relative to the integrated radiative forcing over the same time horizon for a unit emission of CO_2. By normalizing to CO_2, emissions for the component can be given in CO_2 equivalent emissions. The equivalence is only for the selected emission metric and time horizon, and does not imply equivalence of the corresponding climate change responses.. Studies of emission metrics are often based on separate 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 separately for emissions in summertime and wintertime. The same trends for radiative forcing discussed above are also found for the emission metrics.

The absolute form (i.e., not normalized to CO_2) of GTP, called AGTP,describes the relationship between emissions and the development of global mean temperatures. 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. However, regional differences in temperature perturbations are accounted for when estimating changes in global temperature with models. 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 a factor 4.9 and 3.4 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 for global emissions the magnitude of the cooling from SO_2 is larger than the impact of BC.

It must be mentioned that the parameters behind the ARTP concept are largely based on one 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.Other emission metrics have also been developed. Shine et al. (2015) presented Global Precipitation-change Potential (GPP), which is a metric linking emissions with global precipitation changes. Black carbon stands out with negative metric values for sustained emissions, indicating reduced precipitation due to the fast response of atmospheric absorption of BC. Allen et al. (2016)discussed how GWP better can be used to compare short lived climate forcers with long-lived components such as CO_2. They propose to compare a one-off pulse emission of a cumulative component such as CO_2 with a an indefinitely sustained change in the rate of emission of short lived climate forcers.

5 The current status of organic carbon research

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. (2017b) 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 from -1.9 to -0.1 W/m^2 (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. (2013b). 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. (2015b) 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. (2015b) 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. (2015b) 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 presented in part 2 of this report.

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.

Part 2: Assessment and regional perspective

1 Summary and Introduction

In Part 1 of this report, we summarized recent research on the present climate impacts of anthropogenic emissions of black carbon (BC) and organic carbon (OC). In this second part, we present our assessment of the global, regional and sectorial potential of BC and OC climate change mitigation through emission reductions. Our conclusions are based on the literature summarized in Part 1, combined with dedicated analyses.

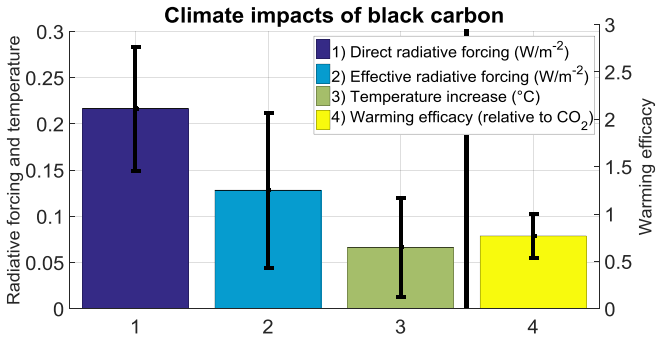

Figure 1: The current climate impacts of BC, from radiative forcing to temperature, based on results from 5 recent climate model simulations (Stjern et al., 2017a). See Part 1.

The most important points from Part 1 of this report are that:

- Black carbon consists of dark-colored carbon 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 have a range of direct and indirect climate impacts.
- The strength of the climate impacts of BC and OC 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.
- The atmospheric residence time of black carbon is likely 3-5 days after emission, which is shorter than calculated by most recent global climate models.
- The global temperature impact of current anthropogenic BC emissions is around +0.1°C. This estimate is based on state-of-the-art climate models which include indirect and semi-direct effects of BC, as well as the effect of BC on snow.
- Very few studies have examined the temperature impact of organic carbon, but one recent multi-model study estimated it at around -0.1°C.
- Although the globally averaged temperature impacts of BC and OC roughly cancel each other, there are large regional differences in the balance between their climate effects.
- Current emissions of black carbon and organic carbon also affect precipitation. Recent studies estimate that their global effects on precipitation are marginal, but that they may still be significant regionally.

Here in Part 2, we use these conclusions to assess differences between emission regions and sectors in terms of climate impact of BC. As there are fewer results available for OC, we use (where possible) the ratio of (warming) BC to (cooling) OC emissions in a region, or sector, to discuss the net temperature effect of mitigation measures. We emphasize here that the conclusions in the following pages are based on our assessment guided by recent literature, and as such are not necessary representative of the whole research community.

In summary, we find that:

- **The climate impacts of aerosols emitted in a given region may be both local and remote.** There is no direct connection between the pattern of emission, radiative forcing and temperature change. The sensitivity of global temperature to black carbon emissions also differs by region. Hence, the mitigation potential of BC and OC (in terms of global temperature change) needs to be separately considered for each emission region.
- **Presently, East Asia, South Asia and Southern Africa are the main BC emission regions, each causing around 0.01 °C of global warming.** The Russia, Belarus, Ukraine and Caucasus region represents a similar amount of warming, but for much lower emissions (25% of those in East Asia), illustrating the regional difference in sensitivity to emissions.
- **The residential sector (fuel for cooking and heating) emits the most BC, globally and in the main emissions regions.** In East Asia, the energy sector also contributes strongly.
- **The mitigation potential of warming BC is strongly dependent on co-emission with cooling OC.** Transportation stands out as the sector with lowest co-emissions of OC, suggesting higher mitigation potential in regions where transportation contributes significantly to global BC emissions. North Africa and the Middle East, East Asia and South America are examples.
- **BC has likely been a contributor to the recent strong Arctic warming.** The sensitivity of Arctic temperature is highest for high latitude source regions, notably Europe and the Russia, Belarus, Ukraine and Caucasus regions. In absolute impact, East Asia and South Asia are the strongest contributors to Arctic warming through BC emissions.
- **The climate impact of aerosols likely extends beyond temperature, to precipitation and extreme weather.** However, we find that present knowledge is insufficient to quantify the impacts of present BC and OC emissions on global or regional precipitation patterns. This is an area of very active research, and will likely have progressed when the IPCC 6th Assessment Report is published.

The rest of the report is structured as follows: We first introduce the cause-and-effect chain from aerosol emissions to climate impact, and use it to motivate and explain the methodology of our assessment. Next we present the regions to be considered, together with numbers from recent emission inventories, before showing the temperature impacts of the emissions in each region and sector. We then give a summarized list of each region. Finally, we give some remarks on specific regional processes that may be of importance, but where the literature is insufficient to provide a full assessment.

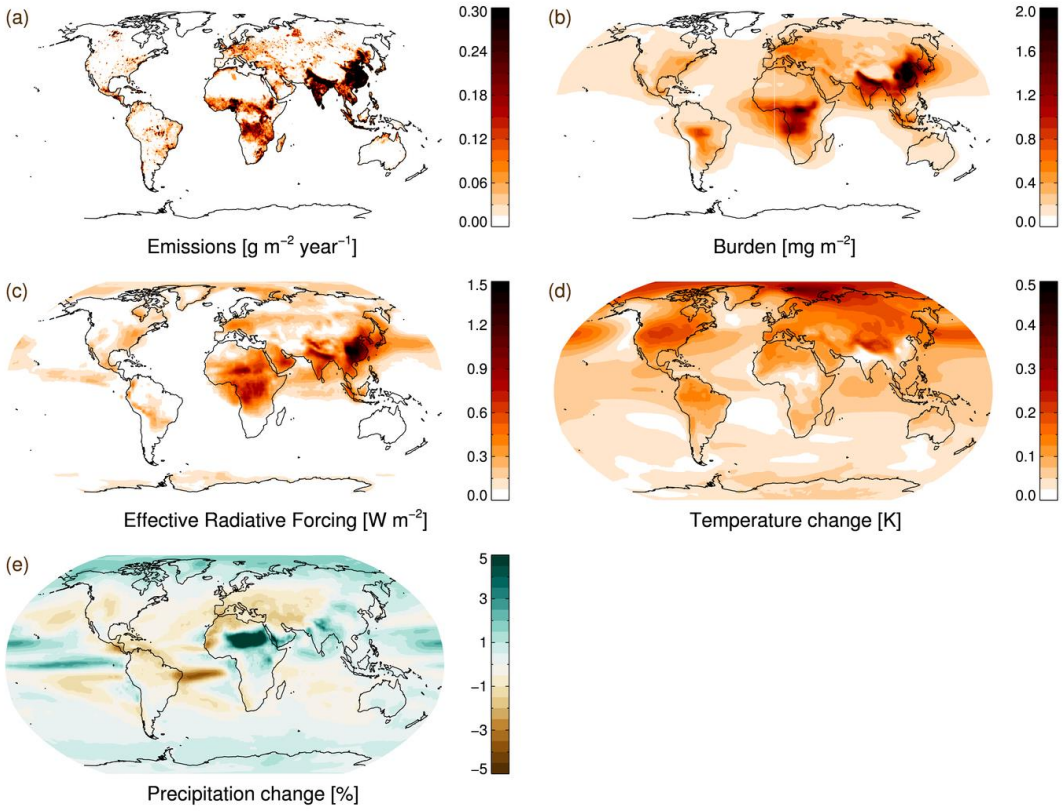

Figure 2: The cause-and-effect chain of the climate impacts of black carbon; from emissions (a), through burden (b) and radiative forcing (c), to changes in temperature (d) and precipitation (e).

2 Methodology

The path from BC and OC emissions to their climate effects goes through multiple steps. In Figure 2, we illustrate how the impact patterns change when we move from emissions to climate impact, so that emissions in a given region can be expected to affect the climate far from their origin. Panel (a) shows the present pattern of BC emissions, for year 2014 (Hoesly et al., 2018). These emissions are then transported via the atmospheric circulation, to reach locations over much of the globe (aerosol burden, panel (b) (Myhre et al., 2013a)). From these locations, the particles change the energy absorption of the atmosphere i.e., radiative forcing, (panel (c) (Stjern et al., 2017a)). Note how the forcing pattern is somewhat different to the burden pattern, as the forcing is affected by factors such as how white the surface is, how high up in the atmosphere the aerosols are, and how clouds change in response to the presence of aerosols.

Finally, the climate effects of the aerosol emissions; temperature (d) and precipitation (e) (Stjern et al., 2017a); again have substantially different patterns. The reason is that the energy added to the climate system by the forcing, is also transported via atmospheric circulation. A change in one location may, in principle, affect the climate over much of the globe, and an equal change in different regions may affect global climate differently.

For this assessment, we need to know both the regional emissions, and the balance between (mainly warming) BC and (cooling) OC for each emission sector in each region. Combined with cause-and-effect information like that shown in Figure 2, we can evaluate the importance of each region for global climate.

Our methodology is as follows:

- We take BC emission estimates from recent inventories, and subdivide into the regions of interest (to be defined below). We use a combination of CEDS emissions (available through year 2014; to be used e.g. as input for the CMIP6 coordinated climate model simulations prepared in advance of the upcoming IPCC 6th Assessment Report) (Hoesly et al., 2018), and emissions from the recent EU FP7 project ECLIPSE (available through 2010) (Klimont et al., 2017). The inventories are broadly similar, except that the CEDS emissions capture additional trends over the period 2010-2014. We use them interchangeably here as they were used in different simulations that we base our assessment on. The minor differences between the emission sets do not significantly affect our conclusions.
- We then simulate the transport of aerosols from emissions in each region, using the model OsloCTM2 (Lund et al., 2017). This gives us the regional contributions to the global distribution of BC aerosols, both horizontally and vertically.
- Next, we calculate the temperature impact of emissions from each region (Samset and Myhre, 2015a), using recent estimates of the temperature effect of BC at a given location and altitude. This is a simplified approach, used and verified in previous studies (e.g. (Lund et al., 2017)), that combines the power of full, global climate model simulations with the detail level only achievable through use of regional and sectorial emission inventories.
- To be consistent with recent literature, we ensure that the temperature impact from the sum of all emissions corresponds to the +0.1 °C estimated in Part 1. This minimizes the influence of the specific climate model used in the previous steps. This also, makes our temperature estimates consistent with those taking into account all BC-climate interactions present in the more complex, global models. These include the direct and semi-direct (rapid adjustment) effects of BC, the modification of cloud whiteness due to aerosols, and, for a number of the underlying models, the impact of BC deposition on snow (albedo effect). We note that in recent multi-model assessments, inclusion of BC deposition in snow has not been found to cause strong differences between calculated BC global temperature impact (Stjern et al., 2017a).
- Finally, as similar calculations are not available for OC, we use the ratio of BC to OC emissions (discussed below) to assess the combined, regional and sectorial, potential of mitigation of carbonaceous aerosols in terms of global temperature. Such an assessment should be taken as a tentative assessment only, and dedicated studies of the climate impacts of OC undertaken in the future.

3 Regions and emissions

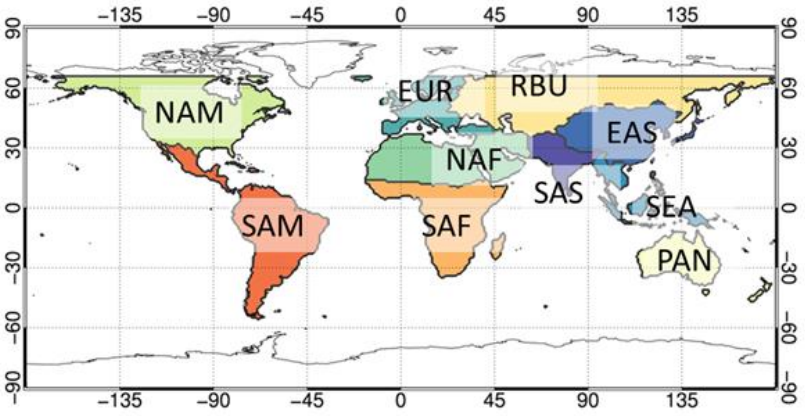

Figure 3: Emission regions used in the present assessment, consistent with those used by the HTAP collaboration (Janssens-Maenhout et al., 2015).

We now move on to show temperature impacts of emissions in different regions and sectors. We divide present BC and OC emissions into nine regions; see Figure 3. The regions are North America (NAM: US and Canada up to 66°N), South America, Mexico, and Central America (SAM), Europe (EUR: Western Europe, Eastern members of EU, and Turkey, up to 66°N), Middle East and North Africa (NAF), Southern Africa (SAF, Southern and Central Africa), Russia, Belarus, Ukraine and Caucasus (RBU, countries up to 66°N), East Asia (EAS: China, Japan, and Korea), South Asia (SAS: India, Pakistan and Bangladesh), Southeast Asia (SEA), Pacific, Australia, and New Zealand (PAN).

Figure 4 (top panel) shows the present day (year 2014) emissions of BC from each region, ordered from high to low contributions to global emissions. The bars are further divided into contributions from different industrial sectors: Energy, Industry, Transportation, Residential, Waste and Shipping.

We see that the East Asia region, which is dominated by China, is currently the largest emitter of BC. Within the region, the energy and residential (i.e. fuels for cooking and heating) sectors dominate. The South Asia (mainly India) and Southern Africa regions follow, each contributing with around half the combined East Asian emissions. In both regions, the residential sector dominates. In the remaining lower emission volume regions, the transportation and residential sectors are the main contributors.

Next, the bottom panel of Figure 4 shows the ratio of BC to OC emissions within each region, and for each industrial sector. BC is often co-emitted with OC and other cooling components, which will reduce or even reverse the warming impact of the BC emissions. Hence, mitigation efforts aimed at reducing global temperature should focus on sources and activities with large BC emissions and small emissions of the cooling components. Emissions that are rich in BC and low in OC have a high BC/OC ratio. In general, the higher the BC/OC ratio, the more efficient reductions will be at reducing global temperature, since cooling OC will be affected to a lesser degree. Regional differences may however come into play, so the BC/OC ratio should be used as a rule-of-thumb only. Figure 4 shows that mitigation in the transportation sector can be beneficial in terms of reducing the global temperature, as can the shipping and industry sectors. Measures targeting the residential and waste sectors, however, will have a relatively larger impact on co-emitted OC, and therefore a lower potential benefit in terms of global temperature. We note that the ratio is calculated as the amount of BC to OC emission, in mass units of millions of tonnes per year, not as a ratio of the climate impact of BC to that of OC. Hence, a ratio of 1 does not mean that mitigation

will have a temperature effect of zero. We also stress that although a BC/OC ratio is low, this does not negate the importance of reducing emissions to improve indoor and outdoor air quality.

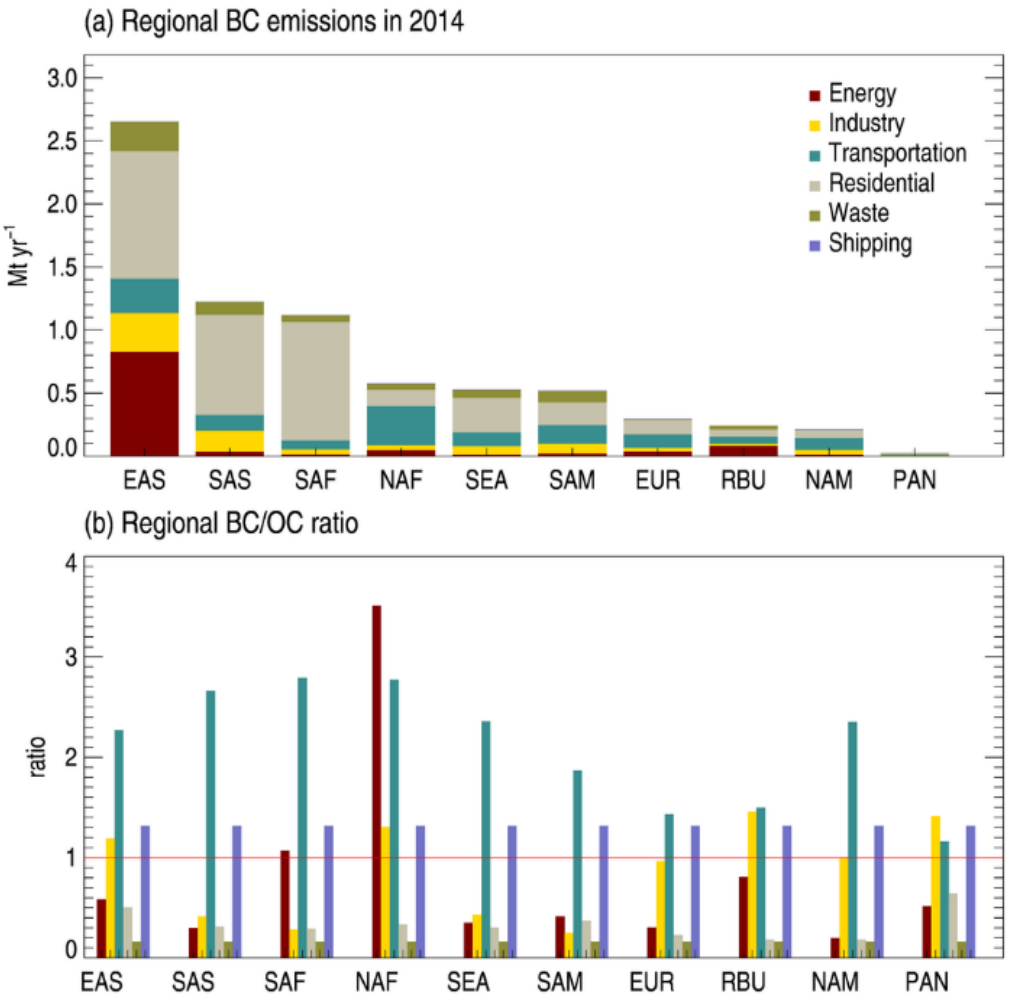

Figure 4: Regional and sectorial BC emissions (top), and the ratio of BC to OC emissions within each region and sector (bottom). Based on (Hoesly et al., 2018).

4 Global and regional temperature impacts

Recent studies show that the global temperature increase caused by current BC emissions is about 0.1 °C (Stjern et al., 2017a; Baker et al., 2015a), while current emissions of OC leads to a cooling of similar magnitude. It follows that the global impact from each region will be modest. However, the regions are not equal in contribution, and local impacts may be much stronger that the global average.

The emissions shown in the previous section, combined with climate modelling and recent literature as described above, allow us to estimate the contribution from each region. The global temperature response for emissions in a region is driven by two factors: How large the emissions are and how sensitive the climate is to emissions in each region.

Figure 5 (top panel) shows the global temperature effect of regional BC emissions, still ordered from high to low emissions. The regions East Asia, South Asia and Southern Africa all have strong impact, mainly due to large emissions sources in those areas. The RBU region (Russia, Belarus, Ukraine and Caucasus) has a similar global temperature impact, while representing a much smaller source of emissions. This illustrates that the global temperature impact is not only determined by the amount of emissions, but also by transport patterns, surface albedo and other factors, as indicated by Figure 2 above. For RBU, the reason is its high latitude, where warming BC emissions will contribute to the amplified Arctic warming, and that the particles are transported over regions with high surface albedo (white surfaces), where BC is extra efficient at absorbing energy. Broadly, the lower part of Figure 5, which shows the global temperature impact per unit emission in the source region, demonstrates that the global climate is more sensitive to emissions from Africa and

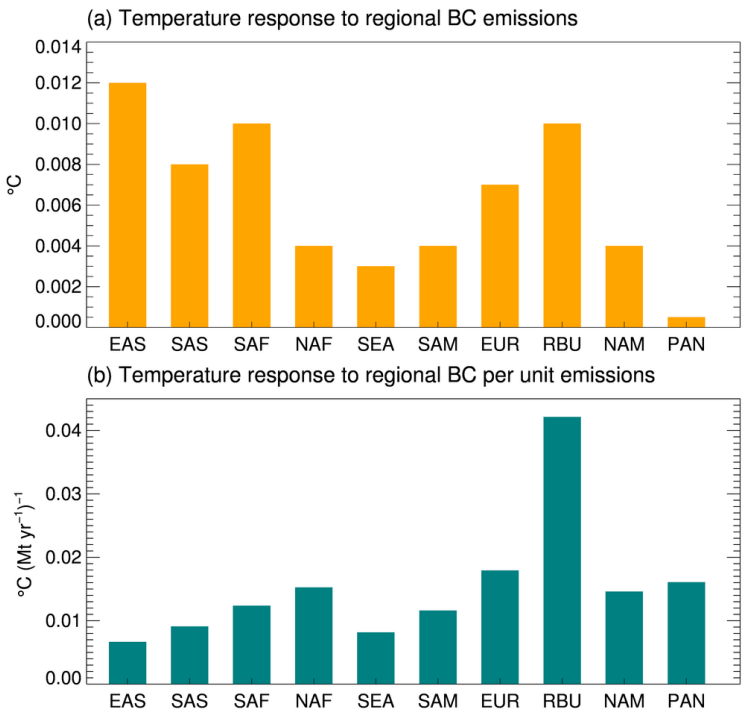

Figure 5: The global temperature effect of current (2014) regional BC emissions (top), and the global temperature change per Tg of regional emissions (bottom).

the Middle East, Europe, the Americas and Australia, than to East, South and South East Asia. The RBU region stands out with the clearly highest sensitivity, although the total emission volume from that region is low in our present inventories.

As shown above, emissions from the East Asia, South Asia and Southern Africa regions are dominated by the residential sector, which also has a low BC to OC ratio. This means that measures targeting these regions and/or sectors may give less reduction in global temperature *per kg BC removed* , than e.g. the Middle East, North America and Europe, where the BC-dominated transportation sector contributes more, because the co-emitted OC is in general reduced simultaneously. However, the overall effectiveness of emission reductions in a given region also depends on the *absolute magnitude* of emissions.

Below, we discuss the results shown in Figures 4 and 5 for each individual region.

5 Regional and sectorial perspectives

In the following, we briefly summarize the results for each region, and give some additional perspectives where relevant.

5.1 North America (NAM)

This region contributes 2.6 % of the global anthropogenic BC emissions. The largest sector is transportation, which constitutes 45 % of the total regional emissions and has a BC/OC ratio of 2.4. The BC/OC ratios for energy and residential emissions are among the lowest of the regions considered at 0.20. North American BC emissions contribute 0.004 °C to global warming, 6 % of the total impact of all anthropogenic BC emissions. Since 1950 BC emissions in the region have already decreased by 50 %, hence the potential for further large emission cuts is more limited than in other regions.

5.2 South America, Mexico, and Central America (SAM)

This region combined contributes 6.5 % of the global BC emissions, with emissions in South America around 50 % higher than in Mexico and Central America. Transportation and residential emissions are of equal magnitude in South America, while residential emissions makes up the largest fraction of Central America emissions. The BC/OC ratio of these two sectors is 1.8 and 0.4, respectively. Emission cuts in the transport sector, therefore, will yield more cooling per unit mass, as the proportion of warming BC aerosols are larger here than in the residential sector. In 2010,

emissions in the region contributed a warming impact of 0.004 °C, 6 % of the total impact of all anthropogenic BC emissions.

5.3 Europe (EUR)

European emissions presently contributes 3.7 % of the global BC emissions. The transport and residential sectors both constitute around 37% and have BC/OC ratios of 1.43 and 0.23. As for North America, emissions in Europe have shown a negative trend over the past decades. BC emissions from Europe contribute 0.007 °C to global warming (11 % of the total impact of all anthropogenic BC emissions) and the region is the second most important in terms of sensitivity, or temperature impact per emission. Since 1950 BC emissions in the region have decreased by 40 %, which contributes to limit the potential for further mitigations.

5.4 Middle East and North Africa (NAF)

Emissions in North Africa and the Middle East contributes 7.2 % of the global BC emissions. Emissions in the Middle East are about twice as high as in North Africa and the sectoral split is also quite different. Residential emissions make up only 5% of Middle Eastern emissions, but 40% of North African. Transportation is the dominating source of BC in the Middle East (70% of the total), followed by the energy sector (11%). The Middle East is the only region where the BC/OC ratio is larger than 1 for all sectors except waste burning, and is 2.7 and 3.8 for the two largest sectors. Combined, BC emissions in the region contribute to a warming of 0.004 °C, 6 % of the total impact of all anthropogenic BC emissions. This value is for emissions in 2010; these are 50 % lower than the updated estimates for 2014.

5.5 Southern Africa (SAF)

Southern Africa contributes 14 % of the global BC emissions, making it the third largest of the regions considered. We note, however, that this is a large aggregated region and there are likely large differences between countries. Almost all emissions come from the residential sector, constituting 84% of the total regional. In fact, a quarter of the global residential BC is emitted in Southern Africa. Remaining sectors make up 1-6 % each. The residential sector generally has a low BC/OC ratio (here 0.3), but as noted above, reducing emissions from this sector will still be beneficial to indoor and outdoor air quality. In 2010, regional BC emissions contributed 0.01 °C to global warming, 16 % of the total impact of all anthropogenic BC emissions. The sensitivity is slightly lower than for emissions in North Africa, likely because of differences in rainfall which affects aerosol transport.

5.6 Russia, Belarus, Ukraine and Caucasus (RBU)

This region contributes 3 % of the global BC emissions, dominated by emissions in Russia. In contrast to the other regions considered, the dominating sector here is energy, contributing 34% of the total regional BC emissions, followed by equal contributions from residential and transportation

(23 %). The energy sector is relatively BC-rich with a BC/OC ratio of 0.75, while the transport sector has a BC/OC ratio of 1.5. In 2010, regional BC emissions contributed 0.01 °C to global warming, 16 % of the total impact of all anthropogenic BC emissions. This is the same order magnitude as contributions from South Africa and Asia despite 70-90 % lower emissions, showing the high sensitivity of temperature response to emissions in this region.

5.7 East Asia (EAS)

East Asia is presently the largest BC source region and contributes 33 % of the global BC emissions. The residential sector gives the largest contribution (38%), followed by energy (31 %). BC emissions from the energy sector in East Asia constitutes 70 % of global energy-related BC emissions. Transportation and industry constitute around 10 % of the total regional emissions each; hence there is significant potential for emission cuts in all sectors. The BC/OC ratio of the energy and residential sectors is 0.5. Hence, while there is significant potential for large cuts in BC emissions in East Asia, the reduced warming will be partly compensated by reduced cooling from reduced OC. In 2010, BC emissions in the region contributed 0.012 °C to global warming, 20 % of the total impact of all anthropogenic BC emissions. The emission estimate for 2010 is 30 % lower than for 2014, hence this impact has increased. The sensitivity is among the lowest for the regions considered, but due to the magnitude of current emissions, emission reductions will be important. Moreover, emissions have increased rapidly in recent decades and are a factor 6 higher than in 1950.

5.8 South Asia (SAS)

This region presently contributes 15% of the global BC emissions, making it the second largest considered. The by far most important sector is residential, constituting 65% of the total regional emissions, while transport and industry make up around 10% each. As in East Asia, emissions have increased strongly in recent decades. South Asian BC emissions in 2010 contributed 0.008 °C to global warming, 13 % of the total impact of all anthropogenic BC emissions. As discussed below, changes in the monsoon circulation has been linked to aerosols emissions in South Asia.

5.9 Southeast Asia (SEA)

Southeast Asia contributes 6.6 % of the global BC emissions. The region comprises Indonesia, Malaysia, Singapore, Thailand, Myanmar and Vietnam. Again, residential emissions are most important (52% of the total in the region), followed by transportation (21%). The waste sector is also relatively more important here than in neighboring regions (12%). Southeast Asian BC emissions contributed 0.003 °C to global warming, 5 % of the total impact of all anthropogenic BC emissions, with a lower than average sensitivity.

5.10 Pacific, Australia, and New Zealand (PAN)

This region is small and contributes only 0.3 % of the global BC emissions. Consequently the temperature impact is also small at only 0.0005 °C, 1 % of the total impact of all anthropogenic BC

emissions. In terms of warming per unit emissions, the region is comparable to Europe and North America, and hence among the most sensitive.

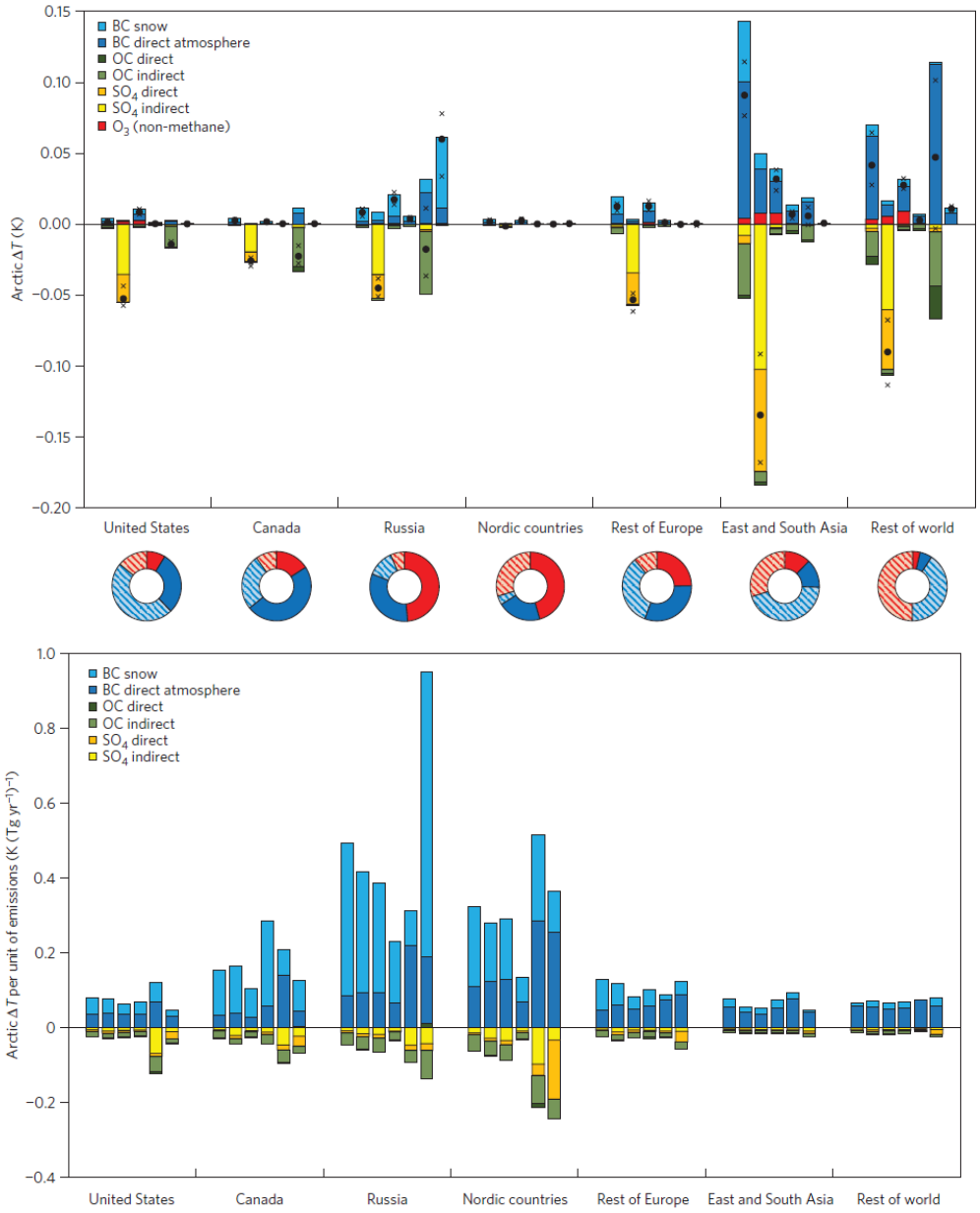

Figure 6: The influence of BC (blue), OC (green) and other short lived climate forcers on Arctic temperature. Top: Absolute changes, due to present day emissions. Bottom: Sensitivites, i.e. temperature change per million tonnes of emissions. From (Sand et al., 2016).

5.11 Arctic (not present in the maps above)

The Arctic is warming faster than the global average (Hartmann et al., 2013; Cowtan and Way, 2014; Laîné et al., 2016). While this trend is dominated by warming from greenhouse gases,

aerosols play an important role (Dou and Xiao, 2016). This is especially true for BC because of its strong snow albedo effect, involving additional warming due to reduced sea ice and snow cover and due to BC deposited on snow. The Arctic has been found to be particularly sensitive (that is, a larger temperature increase per kg emitted) to emissions occurring within the region. This is connected to the dynamics of the atmosphere surrounding the Arctic; emissions from regions at high latitudes are most effectively transported into the region and can be deposited on ice and snow. As seen in the bottom panel of Figure 6, emissions in Canada, Russia and Nordic countries consequently cause a higher temperature response in the Arctic than emissions further south. Presently, however, these emissions are small and the BC abundance is therefore determined by long-range transport from source regions outside. BC emissions further south, for instance in India and China, are lofted and transported into the Arctic at higher altitudes, where they warm the atmosphere at those altitudes but also acts as a shield, blocking sunlight from the surface. The stable Arctic atmosphere hinders mixing of the heat and of the particles themselves down to the Arctic surface, so the total effect is a limited direct influence on the surface temperature. However, BC emissions also affect the Arctic without ever reaching the region through localized heating and subsequent transport of warm air and moisture to the north. This impact, reflected for Asia and South Asia in the top panel of Figure 6, is stronger the higher the (remote) emissions. Therefore, in order to reduce Arctic warming it is necessary to reduce BC emissions also in remote source regions, regardless of whether or not these emissions even reach the Arctic through long-range transport.

5.12 Shipping

For all regions, shipping constitutes a small fraction (less than 2 %) of the total BC emissions (Comer et al., 2017; Hoesly et al., 2018). Hence, despite a BC/OC ratio of 1.3, the potential for achieving notable BC reduction from this sector initially appears limited compared with other sectors. However, we note that the magnitude of shipping emissions are uncertain, and that the location and geographical pattern of shipping emissions differs from other sectors. In particular in the Arctic, shipping emissions may represent a significant regional source. (See e.g. Figure 5 in Comer et al. (2017).) As an example, one study found that when shifting shipping lanes between Europe and Asia from the Suez canal to the Arctic, reduced BC emissions due to the shorter distance resulted in global cooling, but the deposition of BC on snow in the Arctic (albedo effect) gave a compensating warming (Fuglestvedt et al., 2014). Conversely, a reduction in shipping emissions near the Arctic can be expected to have a strong temperature impact per gram, as discussed above.

6 Discussion

6.1 Uncertainties and limitations

For this assessment, we have assumed that present day emissions of BC and OC are known, and that the atmospheric transport and climate effects of aerosols can be captured with up-to-date climate models. We emphasize, however, that the uncertainties in both emission inventories and the modelling of aerosol-climate interactions are still significant. While we have based our conclusions on the best available science, there is ongoing debate as to both the global and regional magnitude of emissions, and the total climate effect of aerosols. Furthermore, the magnitude of the temperature impact of BC on snow in the Arctic (often termed the albedo effect) is not well known. In the key studies used here to estimate the global mean temperature impact of BC, the deposition of BC on snow was included in a subset of the models. No significant difference was found between models that do, and do not, include the albedo effect, however. In the simplified methodology used to calculate temperature responses, BC on snow is not included.

6.2 Impacts on precipitation

Anything that changes the energy balance of the atmosphere, such as aerosols, will also affect precipitation. At present, both surface temperature and precipitation change are strongly affected by anthropogenic aerosol emissions, of which BC and OC are a key part. So, while SO_2 emissions are likely the main cause of the present climate impacts of aerosols, changes to BC and OC emissions are also likely to have regional impacts (see (Samset et al., 2018) and references therein).

In general, when surface temperature rises, so will the average amount of rainfall. Black carbon is however special in this regard. Since it absorbs solar radiation, it heats the air wherever it is present – which is often at high altitudes. This changes the stability of the atmosphere, leading rather to a reduction in rainfall than an increase. Recent literature concludes that the present emissions of BC lead to a reduction of -0.1 % to -0.2 % in global, annual mean precipitation, though with a large spread between models and studies (Stjern et al., 2017a; Baker et al., 2015a). One reason for this spread is that precipitation formation depends on local variations in topography, and other features on a smaller or faster scale than climate models are able to resolve. Clouds and cloud processes leading to precipitation have to be approximated in today's models. Precipitation is also highly dependent on circulation patterns and natural variability, which complicates the system and our ability to simulate it. Our assessment is therefore that further work is required before robust conclusions can be drawn about the (global or regional) precipitation impact of BC or OC emissions; however there is little doubt that such a connection exists in principle.

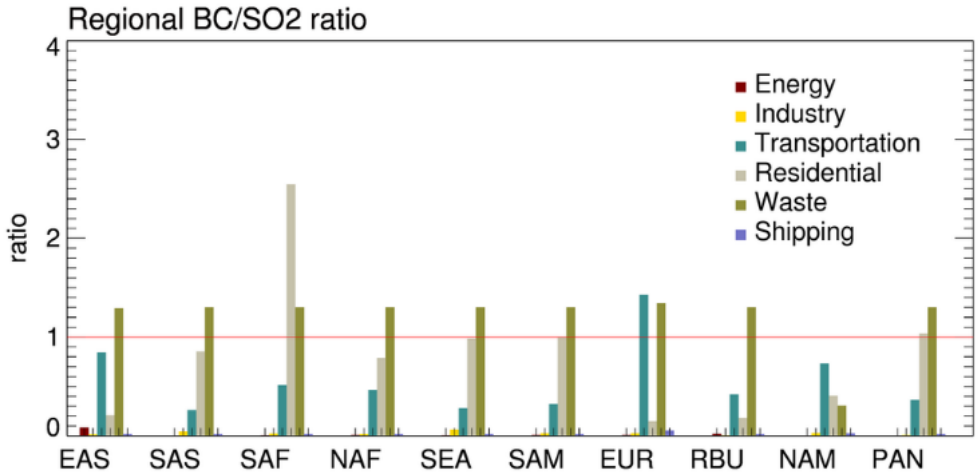

Figure 7: Ratio of BC to SO2 emissions, for the regions and sectors considered here. Based on (Hoesly et al., 2018).

6.3 Co-emissions of BC and OC with SO_2

As discussed above, BC and OC are often co-emitted, so that measures targeting one emission type will also affect the other. BC and OC are also co-emitted with SO_2. We note here that of the present anthropogenic aerosols, sulphate/SO_4 (which is converted from SO_2 emissions in the atmosphere) is presently thought to have the strongest temperature impact. In total, anthropogenic emissions of BC, OC and SO_4 were recently evaluated to provide a net cooling of -0.5 to -1.1 °C (Samset et al., 2018). This means that, as the temperature impacts of BC and OC broadly cancel out, it is the temperature impact of SO_4 emissions dominates.

Any proposed measures targeting aerosol emissions, in particular if they are targeted towards global temperature goals, should therefore also consider the impact on SO_4 and its associated global cooling. In Figure 7, we show the ratio of BC to SO_2 emissions from the regions and sectors considered here. Broadly, the residential and waste sectors have relatively large BC emissions compared to SO_2, while the energy, industrial and shipping sectors are SO_2 dominated. Some regional differences exist, but the overall picture is similar over most of the globe. Note, however, that it is not possible to draw conclusions about e.g. the relative importance of temperature impacts from SO_4 and BC from this kind of figure. As SO_4 is primarily produced in the atmosphere some time after emission, and also strongly affects clouds, its net climate impact can only be assessed with dedicated studies using Earth System Models. To the extent that such simulations exist, they give widely varying results (Kasoar et al., 2016; Liu et al., 2018).

6.4 Air quality and health

The present report has focused on the climate impact of BC and OC emissions, mainly in terms of temperature. We wish to note, however, that an important motivation for reductions in aerosol emissions remains health and air quality (see e.g. Zhang et al. (2017a)). A low temperature impact from emissions in a given region or sector, or a low BC/OC ratio, does not mean that the air quality benefits from mitigation measures are low. Hence, in order to identify mitigation measures with optimal co-benefits, aerosol climate impact studies should not be taken as proxies for air quality, or vice versa. Instead, combined, multi-disciplinary studies are needed.

6.5 Incentives to mitigate BC and OC emissions

The incentives to mitigate aerosols differ from the incentives to mitigate CO_2 and other long-lived components due to the shorter lifetimes of the aerosols, and their differing local and regional climate impacts and co-benefits. Primarily due to large health co-benefits that accrue to the country undertaking a mitigation action, a large share of the technical mitigation potential for BC is in the national self-interest (Aakre et al., 2017). The new insights into the impacts of BC and OC on regional (and local) precipitation and extreme events are likely to strengthen this finding, as they provide additional incentives for countries to mitigate their own emissions. Incorporating the fact that BC is often co-emitted with OC and other cooling components has less straightforward implications for incentives, as this implies simultaneous reduction in climate benefits (mitigating the cooling components will increase or reverse the cooling impact of mitigating BC emissions) and increase in co-benefits (as reducing emissions of OC and other cooling components also has positive health benefits). Whether the co-emissions on balance increase or decrease incentives to mitigate BC is an empirical question, but given the much larger contribution of health benefits to the total benefits of mitigation (Aakre et al., 2017), it is likely that incentives increase on aggregate. Given the substantially different rates of co-emissions across sectors, the implications might differ by sector.

6.6 Projected future emissions

Existing scenarios project decreases in global emissions of aerosols and precursors over the 21st century (van Vuuren et al., 2011). The magnitude of the reductions vary across scenarios, reflecting assumptions about socio-economic and technological trends, but it is generally assumed that air quality policies will be successfully implemented and that technologies to control emissions will continue to evolve (Rao et al., 2017). However, the timing and strength of projected emission reductions, as well as the stringency of currently adopted policies, differ considerably across regions. As noted above, such regional differences are already seen. For instance, emissions of SO_2 are have decreased strongly over the past decade in China, but increased in India. In contrast, BC emissions continue to increase in both these regions. Moreover, maximum technically feasible reduction (MTFR) scenarios show that there exist significant potential for reductions beyond what is achieved through currently adopted legislation in most, if not all, sectors and regions.

7 Appendix: Definitions of emission sectors

Table 1. CEDS working sectors and fuels (CEDS v2016-07-26). RCO indicates the "residential, commercial, other" sector.

CEDS working sectors		
Energy production	1A2g_Ind-Comb-other	**RCO**
1A1a_Electricity-public	2A1_Cement-production	1A4a_Commercial-institutional
1A1a_Electricity-autoproducer	2A2_Lime-production	1A4b_Residential
1A1a_Heat-production	2Ax_Other-minerals	1A4c_Agriculture-forestry-fishing
1A1bc_Other-transformation	2B_Chemical-industry	1A5_Other-unspecified
1B1_Fugitive-solid-fuels	2C_Metal-production	**Agriculture**
1B2_Fugitive-petr-and-gas	2-D_Other-product-use	3B_Manure-management
1B2d_Fugitive-other-energy	2-D_Paint-application	3-D_Soil-emissions
7A_Fossil-fuel-fires	2-D_Chemical-products-manufacture-processing	3I_Agriculture-other
Industry	2H_Pulp-and-paper-food-beverage-wood	3-D_Rice-Cultivation
1A2a_Ind-Comb-Iron-steel	2-D_Degreasing-Cleaning	3E_Enteric-fermentation
1A2b_Ind-Comb-Non-ferrous-metals	**Transportation**	**Waste**
1A2c_Ind-Comb-Chemicals	1A3ai_International-aviation	5A_Solid-waste-disposal
1A2d_Ind-Comb-Pulp-paper	1A3aii_Domestic-aviation	5E_Other-waste-handling
1A2e_Ind-Comb-Food-tobacco	1A3b_Road	5C_Waste-combustion
1A2f_Ind-Comb-Non-metalic-minerals	1A3c_Rail	5-D_Wastewater-handling
1A2g_Ind-Comb-Construction	1A3di_International-shipping	6A_Other-in-total
1A2g_Ind-Comb-transpequip	1A3di_Oil_tanker_loading	6B_Other-not-in-total
1A2g_Ind-Comb-machinery	1A3dii_Domestic-navigation	
1A2g_Ind-Comb-mining-quarying	1A3eii_Other-transp	
1A2g_Ind-Comb-wood-products		
1A2g_Ind-Comb-textile-leather		
CEDS fuels		
Hard coal	Light oil	Natural gas
Brown coal	Diesel oil	Biomass
Coal coke	Heavy oil	

Emission components included in each aggregated sector discussed in this report. Taken from (Hoesly et al., 2018). Similar definitions are used for both sets of emissions used above. (The Agricultural sector has no BC emissions in these inventories, and hence is not discussed above.)

References

Aakre, S., Kallbekken, S., Van Dingenen, R., and Victor, D. G.: Incentives for small clubs of Arctic countries to limit black carbon and methane emissions, Nature Climate Change, 8, 85-90, 10.1038/s41558-017-0030-8, 2017.

Aamaas, B., Hodnebrog, Ø., Samset, B. H., Fuglestvedt, F. S., Myhre, G., and Berntsen, T. K.: Oppdaterte vekfaktorer for BC og OC, Center for International Climate and Environmental Research – Oslo (CICERO), Oslo, Norway, 2015.

Aamaas, B., Berntsen, T. K., Fuglestvedt, J. S., Shine, K. P., and Bellouin, N.: Regional emission metrics for short-lived climate forcers from multiple models, Atmos. Chem. Phys., 16, 7451-7468, 10.5194/acp-16-7451-2016, 2016.

Aamaas, B., Berntsen, T. K., Fuglestvedt, J. S., Shine, K. P., and Collins, W. J.: Regional temperature change potentials for short lived climate forcers based on radiative forcing from multiple models, Atmos. Chem. Phys., 17, 10795-10809, 10.5194/acp-17-10795-2017, 2017.

Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., and Forster, P. M.: New use of global warming potentials to compare cumulative and short-lived climate pollutants, Nature Climate Change, 6, 773, 10.1038/nclimate2998, 2016.

Andrews, T., Forster, P. M., Boucher, O., Bellouin, N., and Jones, A.: Precipitation, radiative forcing and global temperature change, Geophysical Research Letters, 37, n/a-n/a, 10.1029/2010GL043991, 2010.

Baker, L. H., Collins, W. J., Olivié, D. J. L., Cherian, R., Hodnebrog, Oslash, Myhre, G., and Quaas, J.: Climate responses to anthropogenic emissions of short-lived climate pollutants, Atmospheric Chemistry and Physics, 15, 8201-8216, 10.5194/acp-15-8201-2015, 2015a.

Baker, L. H., Collins, W. J., Olivié, D. J. L., Cherian, R., Hodnebrog, Oslash, Myhre, G., and Quaas, J.: Climate responses to anthropogenic emissions of short-lived climate pollutants, Atmos. Chem. Phys., 15, 8201-8216, 10.5194/acp-15-8201-2015, 2015b.

Ban-Weiss, G. A., Cao, L., Bala, G., and Caldeira, K.: Dependence of climate forcing and response on the altitude of black carbon aerosols, Climate Dynamics, 38, 897-911, 10.1007/s00382-011-1052-y, 2012.

Bellouin, N., Baker, L., Hodnebrog, Ø., Olivié, D., Cherian, R., Macintosh, C., Samset, B., Esteve, A., Aamaas, B., Quaas, J., and Myhre, G.: Regional and seasonal radiative forcing by perturbations to aerosol and ozone precursor emissions, Atmospheric Chemistry and Physics, 16, 13885-13910, 10.5194/acp-16-13885-2016, 2016.

Bond, T. C., and Bergstrom, R. W.: Light Absorption by Carbonaceous Particles: An Investigative Review, Aerosol Sci. Tech., 40, 27 - 67, 2006.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, Journal of Geophysical Research: Atmospheres, 118, 5380–5552, 10.1002/jgrd.50171, 2013.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V.-M., Kondo, Y., Liao, H., Lohmann, U., Rasch, P., Satheesh, S. K., Sherwood, S., Stevens, B., and Zhang, X. Y.: Clouds and Aerosols, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Boucher, O., Balkanski, Y., Hodnebrog, Ø., Myhre, C. L., Myhre, G., Quaas, J., Samset, B. H., Schutgens, N., Stier, P., and Wang, R.: Jury is still out on the radiative forcing by black carbon, Proceedings of the National Academy of Sciences, 113, E5092-E5093, 10.1073/pnas.1607005113, 2016.

Cappa, C. D., Onasch, T. B., Massoli, P., Worsnop, D. R., Bates, T. S., Cross, E. S., Davidovits, P., Hakala, J., Hayden, K. L., Jobson, B. T., Kolesar, K. R., Lack, D. A., Lerner, B. M., Li, S.-M., Mellon, D., Nuaaman, I., Olfert, J. S., Petäjä, T., Quinn, P. K., Song, C., Subramanian, R., Williams, E. J., and Zaveri, R. A.: Radiative Absorption Enhancements Due to the Mixing State of Atmospheric Black Carbon, Science, 337, 1078-1081, 10.1126/science.1223447, 2012.
Collins, W. J., Fry, M. M., Yu, H., Fuglestvedt, J. S., Shindell, D. T., and West, J. J.: Global and regional temperature-change potentials for near-term climate forcers, Atmos. Chem. Phys., 13, 2471-2485, 10.5194/acp-13-2471-2013, 2013.
Comer, B., Olmer, N., Mao, X., Roy, B., and Rutherford, D.: Black Carbon emissions and fuel use in global shipping, International Council on Clean Transportation, 2017.
Cowtan, K., and Way, R. G.: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends, Quarterly Journal of the Royal Meteorological Society, 140, 1935-1944, 10.1002/qj.2297, 2014.
Cui, X., Wang, X., Yang, L., Chen, B., Chen, J., Andersson, A., and Gustafsson, Ö.: Radiative absorption enhancement from coatings on black carbon aerosols, Science of The Total Environment, 551-552, 51-56, https://doi.org/10.1016/j.scitotenv.2016.02.026, 2016.
Dou, T.-F., and Xiao, C.-D.: An overview of black carbon deposition and its radiative forcing over the Arctic, Advances in Climate Change Research, 7, 115-122, 10.1016/j.accre.2016.10.003, 2016.
Fuglestvedt, J. S., Dalsoren, S. B., Samset, B. H., Berntsen, T., Myhre, G., Hodnebrog, O., Eide, M. S., and Bergh, T. F.: Climate penalty for shifting shipping to the Arctic, Environ Sci Technol, 48, 13273-13279, 10.1021/es502379d, 2014.
Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M., and Zhai, P. M.: Observations: Atmosphere and Surface, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254, 2013.
Hodnebrog, Ø., Aamaas, B., Berntsen, T. K., Fuglestvedt, F. S., Myhre, G., Samset, B. H., and Søvde, O. A.: Klimaeffekt av norske utslipp av kortlevde klimadrivere, CICERO Senter for klimaforskning, Oslo, Norge, 2013.
Hodnebrog, Ø., Myhre, G., and Samset, B. H.: How shorter black carbon lifetime alters its climate effect, Nat Commun, 5, 10.1038/ncomms6065, 2014.
Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emission Data System (CEDS), Geosci. Model Dev. Discuss., 2017, 1-41, 10.5194/gmd-2017-43, 2017.
Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J.-i., Li, M., Liu, L., Lu, Z., Moura, M. C. P., amp, apos, Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geoscientific Model Development, 11, 369-408, 10.5194/gmd-11-369-2018, 2018.
IPCC: Climate Change: The IPCC Scientific Assessment, edited by: Houghton, J. T., Jenkins, G. J., and Ephraums, J. J., Cambridge University Press, Cambridge, United Kingdom, 1990.
Jacobson, M. Z.: Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, J. Geophys. Res., 115, D14209, 10.1029/2009jd013795, 2010.
Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Dentener, F., Muntean, M., Pouliot, G., Keating, T., Zhang, Q., Kurokawa, J., Wankmüller, R., Denier van der Gon, H., Kuenen, J. J. P., Klimont, Z., Frost, G., Darras, S., Koffi, B., and Li, M.: HTAP_v2.2: a mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution, Atmospheric Chemistry and Physics, 15, 11411-11432, 10.5194/acp-15-11411-2015, 2015.
Jones, A., Haywood, J. M., and Boucher, O.: Aerosol forcing, climate response and climate sensitivity in the Hadley Centre climate model, Journal of Geophysical Research: Atmospheres, 112, n/a-n/a, 10.1029/2007JD008688, 2007.
Kasoar, M., Voulgarakis, A., Lamarque, J.-F., Shindell, D. T., Bellouin, N., Collins, W. J., Faluvegi, G., and Tsigaridis, K.: Regional and global temperature response to anthropogenic SO2 emissions from China in three climate models, Atmospheric Chemistry and Physics, 16, 9785-9804, 10.5194/acp-16-9785-2016, 2016.
Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., and Schoepp, W.: Global anthropogenic emissions of particulate matter including black carbon, Atmospheric Chemistry and Physics Discussion, 10.5194/acp-2016-880, 2016.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., and Schöpp, W.: Global anthropogenic emissions of particulate matter including black carbon, Atmospheric Chemistry and Physics, 17, 8681-8723, 10.5194/acp-17-8681-2017, 2017.
Koch, D., and Del Genio, A. D.: Black carbon semi-direct effects on cloud cover: review and synthesis, Atmos. Chem. Phys., 10, 7685-7696, 10.5194/acp-10-7685-2010, 2010.
Kvalevåg, M. M., Samset, B. H., and Myhre, G.: Hydrological sensitivity to greenhouse gases and aerosols in a global climate model, Geophysical Research Letters, 40, 1432-1438, 10.1002/grl.50318, 2013.
Lack, D. A., Cappa, C. D., Cross, E. S., Massoli, P., Ahern, A. T., Davidovits, P., and Onasch, T. B.: Absorption Enhancement of Coated Absorbing Aerosols: Validation of the Photo-Acoustic Technique for Measuring the Enhancement, Aerosol Science and Technology, 43, 1006-1012, 10.1080/02786820903117932, 2009.
Laîné, A., Yoshimori, M., and Abe-Ouchi, A.: Surface Arctic Amplification Factors in CMIP5 Models: Land and Oceanic Surfaces and Seasonality, Journal of Climate, 29, 3297-3316, 10.1175/jcli-d-15-0497.1, 2016.
Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017-7039, 10.5194/acp-10-7017-2010, 2010.
Lan, Z.-J., Huang, X.-F., Yu, K.-Y., Sun, T.-L., Zeng, L.-W., and Hu, M.: Light absorption of black carbon aerosol and its enhancement by mixing state in an urban atmosphere in South China, Atmospheric Environment, 69, 118-123, https://doi.org/10.1016/j.atmosenv.2012.12.009, 2013.
Liu, J., Scheuer, E., Dibb, J., Ziemba, L. D., Thornhill, K. L., Anderson, B. E., Wisthaler, A., Mikoviny, T., Devi, J. J., Bergin, M., and Weber, R. J.: Brown carbon in the continental troposphere, Geophysical Research Letters, 41, 2191-2195, 10.1002/2013GL058976, 2014.
Liu, J., Lin, P., Laskin, A., Laskin, J., Kathmann, S. M., Wise, M., Caylor, R., Imholt, F., Selimovic, V., and Shilling, J. E.: Optical properties and aging of light-absorbing secondary organic aerosol, Atmos. Chem. Phys., 16, 12815-12827, 10.5194/acp-16-12815-2016, 2016.
Liu, L., Shawki, D., Voulgarakis, A., Kasoar, M., Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Sillmann, J., Aalbergsjø, S. G., Boucher, O., Faluvegi, G., Iversen, T., Kirkevåg, A., Lamarque, J. F., Olivié, D., Richardson, T., Shindell, D., and Takemura, T.: A PDRMIP multi-model study on the impacts of regional aerosol forcings on global and regional precipitation, Journal of Climate, 10.1175/jcli-d-17-0439.1, 2018.
Liu, S., Aiken, A. C., Gorkowski, K., Dubey, M. K., Cappa, C. D., Williams, L. R., Herndon, S. C., Massoli, P., Fortner, E. C., Chhabra, P. S., Brooks, W. A., Onasch, T. B., Jayne, J. T., Worsnop, D. R., China, S., Sharma, N., Mazzoleni, C., Xu, L., Ng, N. L., Liu, D., Allan, J. D., Lee, J. D., Fleming, Z. L., Mohr, C., Zotter, P., Szidat, S., and Prévôt, A. S. H.: Enhanced light absorption by mixed source black and brown carbon particles in UK winter, Nature Communications, 6, 8435, 10.1038/ncomms9435

http://www.nature.com/articles/ncomms9435#supplementary-information, 2015.
Lu, Z., Streets, D. G., Winijkul, E., Yan, F., Chen, Y., Bond, T. C., Feng, Y., Dubey, M. K., Liu, S., Pinto, J. P., and Carmichael, G. R.: Light Absorption Properties and Radiative Effects of Primary Organic Aerosol Emissions, Environmental Science & Technology, 49, 4868-4877, 10.1021/acs.est.5b00211, 2015.
Lund, M. T., Berntsen, T. K., Heyes, C., Klimont, Z., and Samset, B. H.: Global and regional climate impacts of black carbon and co-emitted species from the on-road diesel sector, Atmospheric Environment, 98, 50-58, https://doi.org/10.1016/j.atmosenv.2014.08.033, 2014.
Lund, M. T., Berntsen, T. K., and Samset, B. H.: Sensitivity of black carbon concentrations and climate impact to aging and scavenging in OsloCTM2–M7, Atmospheric Chemistry and Physics, 17, 6003-6022, 10.5194/acp-17-6003-2017, 2017.
Mahajan, S., Evans, K. J., Hack, J. J., and Truesdale, J. E.: Linearity of Climate Response to Increases in Black Carbon Aerosols, Journal of Climate, 26, 8223-8237, 10.1175/jcli-d-12-00715.1, 2013.
Mahmood, R., von Salzen, K., Flanner, M., Sand, M., Langner, J., Wang, H., and Huang, L.: Seasonality of global and Arctic black carbon processes in the Arctic Monitoring and Assessment Programme models, Journal of Geophysical Research: Atmospheres, 121, 7100-7116, 10.1002/2016JD024849, 2016.
Malavelle, F. F., Haywood, J. M., Jones, A., Gettelman, A., Clarisse, L., Bauduin, S., Allan, R. P., Karset, I. H. H., Kristjánsson, J. E., Oreopoulos, L., Cho, N., Lee, D., Bellouin, N., Boucher, O., Grosvenor, D. P., Carslaw, K. S., Dhomse, S., Mann, G. W., Schmidt, A., Coe, H., Hartley, M. E., Dalvi, M., Hill, A. A., Johnson, B. T., Johnson, C. E., Knight, J.

R., O'Connor, F. M., Partridge, D. G., Stier, P., Myhre, G., Platnick, S., Stephens, G. L., Takahashi, H., and Thordarson, T.: Strong constraints on aerosol–cloud interactions from volcanic eruptions, Nature, 546, 485, 10.1038/nature22974, 2017.

Moosmüller, H., Chakrabarty, R. K., and Arnott, W. P.: Aerosol light absorption and its measurement: A review, Journal of Quantitative Spectroscopy and Radiative Transfer, 110, 844-878, http://dx.doi.org/10.1016/j.jqsrt.2009.02.035, 2009.

Myhre, G., Samset, B. H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., Bian, H., Bellouin, N., Chin, M., Diehl, T., Easter, R. C., Feichter, J., Ghan, S. J., Hauglustaine, D., Iversen, T., Kinne, S., Kirkevag, A., Lamarque, J. F., Lin, G., Liu, X., Lund, M. T., Luo, G., Ma, X., van Noije, T., Penner, J. E., Rasch, P. J., Ruiz, A., Seland, O., Skeie, R. B., Stier, P., Takemura, T., Tsigaridis, K., Wang, P., Wang, Z., Xu, L., Yu, H., Yu, F., Yoon, J. H., Zhang, K., Zhang, H., and Zhou, C.: Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations, Atmospheric Chemistry and Physics, 13, 1853-1877, DOI 10.5194/acp-13-1853-2013, 2013a.

Myhre, G., Samset, B. H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., Bian, H., Bellouin, N., Chin, M., Diehl, T., Easter, R. C., Feichter, J., Ghan, S. J., Hauglustaine, D., Iversen, T., Kinne, S., Kirkevåg, A., Lamarque, J. F., Lin, G., Liu, X., Lund, M. T., Luo, G., Ma, X., van Noije, T., Penner, J. E., Rasch, P. J., Ruiz, A., Seland, Ø., Skeie, R. B., Stier, P., Takemura, T., Tsigaridis, K., Wang, P., Wang, Z., Xu, L., Yu, H., Yu, F., Yoon, J. H., Zhang, K., Zhang, H., and Zhou, C.: Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations, Atmos. Chem. Phys., 13, 1853-1877, 10.5194/acp-13-1853-2013, 2013b.

Myhre, G., Aas, W., Cherian, R., Collins, W., Faluvegi, G., Flanner, M., Forster, P., Hodnebrog, Ø., Klimont, Z., Lund, M. T., Mülmenstädt, J., Lund Myhre, C., Olivié, D., Prather, M., Quaas, J., Samset, B. H., Schnell, J. L., Schulz, M., Shindell, D., Skeie, R. B., Takemura, T., and Tsyro, S.: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990–2015, Atmos. Chem. Phys., 17, 2709-2720, 10.5194/acp-17-2709-2017, 2017a.

Myhre, G., Forster, P. M., Samset, B. H., Hodnebrog, Ø., Sillmann, J., Aalbergsjø, S. G., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Iversen, T., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T. B., Shindell, D., Shine, K. P., Stjern, C. W., Takemura, T., Voulgarakis, A., and Zwiers, F.: PDRMIP: A Precipitation Driver and Response Model Intercomparison Project—Protocol and Preliminary Results, Bulletin of the American Meteorological Society, 98, 1185-1198, 10.1175/bams-d-16-0019.1, 2017b.

Nakayama, T., Ikeda, Y., Sawada, Y., Setoguchi, Y., Ogawa, S., Kawana, K., Mochida, M., Ikemori, F., Matsumoto, K., and Matsumi, Y.: Properties of light-absorbing aerosols in the Nagoya urban area, Japan, in August 2011 and January 2012: Contributions of brown carbon and lensing effect, Journal of Geophysical Research: Atmospheres, 119, 12,721-712,739, 10.1002/2014JD021744, 2014.

Peng, J., Hu, M., Guo, S., Du, Z., Zheng, J., Shang, D., Levy Zamora, M., Zeng, L., Shao, M., Wu, Y.-S., Zheng, J., Wang, Y., Glen, C. R., Collins, D. R., Molina, M. J., and Zhang, R.: Markedly enhanced absorption and direct radiative forcing of black carbon under polluted urban environments, Proceedings of the National Academy of Sciences, 113, 4266-4271, 10.1073/pnas.1602310113, 2016.

Petzold, A., Ogren, J. A., Fiebig, M., Laj, P., Li, S. M., Baltensperger, U., Holzer-Popp, T., Kinne, S., Pappalardo, G., Sugimoto, N., Wehrli, C., Wiedensohler, A., and Zhang, X. Y.: Recommendations for reporting "black carbon" measurements, Atmos. Chem. Phys., 13, 8365-8379, 10.5194/acp-13-8365-2013, 2013.

Pokhrel, R. P., Beamesderfer, E. R., Wagner, N. L., Langridge, J. M., Lack, D. A., Jayarathne, T., Stone, E. A., Stockwell, C. E., Yokelson, R. J., and Murphy, S. M.: Relative importance of black carbon, brown carbon, and absorption enhancement from clear coatings in biomass burning emissions, Atmos. Chem. Phys., 17, 5063-5078, 10.5194/acp-17-5063-2017, 2017.

Ram, K., and Sarin, M. M.: Absorption Coefficient and Site-Specific Mass Absorption Efficiency of Elemental Carbon in Aerosols over Urban, Rural, and High-Altitude Sites in India, Environmental Science & Technology, 43, 8233-8239, 10.1021/es9011542, 2009.

Rao, S., Klimont, Z., Smith, S. J., Van Dingenen, R., Dentener, F., Bouwman, L., Riahi, K., Amann, M., Bodirsky, B. L., van Vuuren, D. P., Aleluia Reis, L., Calvin, K., Drouet, L., Fricko, O., Fujimori, S., Gernaat, D., Havlik, P., Harmsen, M., Hasegawa, T., Heyes, C., Hilaire, J., Luderer, G., Masui, T., Stehfest, E., Strefler, J., van der Sluis, S., and Tavoni, M.: Future air pollution in the Shared Socio-economic Pathways, Global Environmental Change, 42, 346-358, https://doi.org/10.1016/j.gloenvcha.2016.05.012, 2017.

Saleh, R., Hennigan, C. J., McMeeking, G. R., Chuang, W. K., Robinson, E. S., Coe, H., Donahue, N. M., and Robinson, A. L.: Absorptivity of brown carbon in fresh and photo-chemically aged biomass-burning emissions, Atmos. Chem. Phys., 13, 7683-7693, 10.5194/acp-13-7683-2013, 2013.

Saleh, R., Marks, M., Heo, J., Adams, P. J., Donahue, N. M., and Robinson, A. L.: Contribution of brown carbon and lensing to the direct radiative effect of carbonaceous aerosols from biomass and biofuel burning emissions, Journal of Geophysical Research: Atmospheres, 120, 10,285-210,296, 10.1002/2015JD023697, 2015.
Samset, and Myhre: Climate response to externally mixed black carbon as a function of altitude, Journal of Geophysical Research: Atmospheres, 120, 2014JD022849, 10.1002/2014JD022849, 2015a.
Samset, B. H., Myhre, G., Herber, A., Kondo, Y., Li, S. M., Moteki, N., Koike, M., Oshima, N., Schwarz, J. P., Balkanski, Y., Bauer, S. E., Bellouin, N., Berntsen, T. K., Bian, H., Chin, M., Diehl, T., Easter, R. C., Ghan, S. J., Iversen, T., Kirkevåg, A., Lamarque, J. F., Lin, G., Liu, X., Penner, J. E., Schulz, M., Seland, Ø., Skeie, R. B., Stier, P., Takemura, T., Tsigaridis, K., and Zhang, K.: Modelled black carbon radiative forcing and atmospheric lifetime in AeroCom Phase II constrained by aircraft observations, Atmos. Chem. Phys., 14, 12465-12477, 10.5194/acp-14-12465-2014, 2014.
Samset, B. H., and Myhre, G.: Climate response to externally mixed black carbon as a function of altitude, Journal of Geophysical Research: Atmospheres, 120, 2913-2927, 10.1002/2014JD022849, 2015b.
Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Andrews, T., Faluvegi, G., Fläschner, D., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J. F., Olivié, D., Richardson, T., Shindell, D., Shine, K. P., Takemura, T., and Voulgarakis, A.: Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study, Geophysical Research Letters, 43, 2782-2791, 10.1002/2016GL068064, 2016.
Samset, B. H., Sand, M., Smith, C. J., Bauer, S. E., Forster, P. M., Fuglestvedt, J. S., Osprey, S., and Schleussner, C. F.: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions, Geophysical Research Letters, 10.1002/2017gl076079, 2018.
Sand, M., Berntsen, T. K., Kay, J. E., Lamarque, J. F., Seland, Ø., and Kirkevåg, A.: The Arctic response to remote and local forcing of black carbon, Atmos. Chem. Phys., 13, 211-224, 10.5194/acp-13-211-2013, 2013a.
Sand, M., Berntsen, T. K., Seland, Ø., and Kristjánsson, J. E.: Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes, Journal of Geophysical Research: Atmospheres, 118, 7788-7798, 10.1002/jgrd.50613, 2013b.
Sand, M., Berntsen, T. K., von Salzen, K., Flanner, M. G., Langner, J., and Victor, D. G.: Response of Arctic temperature to changes in emissions of short-lived climate forcers, Nature Clim. Change, 6, 286-289, 10.1038/nclimate2880

http://www.nature.com/nclimate/journal/v6/n3/abs/nclimate2880.html#supplementary-information, 2016.
Schwarz, J. P., Gao, R. S., Spackman, J. R., Watts, L. A., Thomson, D. S., Fahey, D. W., Ryerson, T. B., Peischl, J., Holloway, J. S., Trainer, M., Frost, G. J., Baynard, T., Lack, D. A., de Gouw, J. A., Warneke, C., and Del Negro, L. A.: Measurement of the mixing state, mass, and optical size of individual black carbon particles in urban and biomass burning emissions, Geophysical Research Letters, 35, n/a-n/a, 10.1029/2008GL033968, 2008.
Schwarz, J. P., Samset, B. H., Perring, A. E., Spackman, J. R., Gao, R. S., Stier, P., Schulz, M., Moore, F. L., Ray, E. A., and Fahey, D. W.: Global-scale seasonally resolved black carbon vertical profiles over the Pacific, Geophysical Research Letters, 40, 5542-5547, 10.1002/2013GL057775, 2013.
Shindell, D., and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century, Nature Geoscience, 2, 294-300, 2009.
Shindell, D., and Faluvegi, G.: The net climate impact of coal-fired power plant emissions, Atmos. Chem. Phys., 10, 3247-3260, 10.5194/acp-10-3247-2010, 2010.
Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., and Stuber, N.: Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases, Climatic Change, 68, 281-302, 10.1007/s10584-005-1146-9, 2005.
Shine, K. P., Allan, R. P., Collins, W. J., and Fuglestvedt, J. S.: Metrics for linking emissions of gases and aerosols to global precipitation changes, Earth Syst. Dynam., 6, 525-540, 10.5194/esd-6-525-2015, 2015.
Stevens, B.: Rethinking the Lower Bound on Aerosol Radiative Forcing, Journal of Climate, 28, 4794-4819, 10.1175/jcli-d-14-00656.1, 2015.
Stjern, C. W., Samset, B. H., Myhre, G., Bian, H., Chin, M., Davila, Y., Dentener, F., Emmons, L., Flemming, J., Haslerud, A. S., Henze, D., Jonson, J. E., Kucsera, T., Lund, M. T., Schulz, M., Sudo, K., Takemura, T., and Tilmes, S.: Global and regional radiative forcing from 20 % reductions in BC, OC and SO4 – an HTAP2 multi-model study, Atmos. Chem. Phys., 16, 13579-13599, 10.5194/acp-16-13579-2016, 2016.
Stjern, C. W., Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Andrews, T., Boucher, O., Faluvegi, G., Iversen, T., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T., Shawki, D., Shindell, D., Smith, C. J., Takemura, T., and Voulgarakis, A.: Rapid Adjustments Cause Weak Surface Temperature Response to Increased Black

Carbon Concentrations, Journal of Geophysical Research: Atmospheres, 122, 11,462-411,481, 10.1002/2017jd027326, 2017a.
Stjern, C. W., Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Andrews, T., Boucher, O., Faluvegi, G., Iversen, T., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T., Shawki, D., Shindell, D., Smith, C. J., Takemura, T., and Voulgarakis, A.: Rapid Adjustments Cause Weak Surface Temperature Response to Increased Black Carbon Concentrations, Journal of Geophysical Research: Atmospheres, n/a-n/a, 10.1002/2017JD027326, 2017b.
Stohl, A., Aamaas, B., Amann, M., Baker, L. H., Bellouin, N., Berntsen, T. K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N., Dusinska, M., Eckhardt, S., Fuglestvedt, J. S., Harju, M., Heyes, C., Hodnebrog, O., Hao, J., Im, U., Kanakidou, M., Klimont, Z., Kupiainen, K., Law, K. S., Lund, M. T., Maas, R., MacIntosh, C. R., Myhre, G., Myriokefalitakis, S., Olivie, D., Quaas, J., Quennehen, B., Raut, J.-C., Rumbold, S. T., Samset, B. H., Schulz, M., Seland, O., Shine, K. P., Skeie, R. B., Wang, S., Yttri, K. E., and Zhu, T.: Evaluating the climate and air quality impacts of short-lived pollutants, Atmospheric Chemistry and Physics, 15, 10529-10566, 10.5194/acp-15-10529-2015, 2015.
van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K.: The representative concentration pathways: an overview, Climatic Change, 109, 5, 10.1007/s10584-011-0148-z, 2011.
Wang, Q., Jacob, D. J., Spackman, J. R., Perring, A. E., Schwarz, J. P., Moteki, N., Marais, E. A., Ge, C., Wang, J., and Barrett, S. R. H.: Global budget and radiative forcing of black carbon aerosol: Constraints from pole-to-pole (HIPPO) observations across the Pacific, Journal of Geophysical Research: Atmospheres, 119, 195-206, 10.1002/2013JD020824, 2014a.
Wang, R., Balkanski, Y., Boucher, O., Ciais, P., Schuster, G. L., Chevallier, F., Samset, B. H., Liu, J., Piao, S., Valari, M., and Tao, S.: Estimation of global black carbon direct radiative forcing and its uncertainty constrained by observations, Journal of Geophysical Research: Atmospheres, 121, 5948-5971, 10.1002/2015JD024326, 2016.
Wang, X., Heald, C. L., Ridley, D. A., Schwarz, J. P., Spackman, J. R., Perring, A. E., Coe, H., Liu, D., and Clarke, A. D.: Exploiting simultaneous observational constraints on mass and absorption to estimate the global direct radiative forcing of black carbon and brown carbon, Atmos. Chem. Phys., 14, 10989-11010, 10.5194/acp-14-10989-2014, 2014b.
Yoshimori, M., and Broccoli, A. J.: Equilibrium Response of an Atmosphere–Mixed Layer Ocean Model to Different Radiative Forcing Agents: Global and Zonal Mean Response, Journal of Climate, 21, 4399-4423, 10.1175/2008jcli2172.1, 2008.
Yttri, K. E., Lund Myhre, C., Eckhardt, S., Fiebig, M., Dye, C., Hirdman, D., Ström, J., Klimont, Z., and Stohl, A.: Quantifying black carbon from biomass burning by means of levoglucosan – a one-year time series at the Arctic observatory Zeppelin, Atmos. Chem. Phys., 14, 6427-6442, 10.5194/acp-14-6427-2014, 2014.
Yu, H., Chin, M., West, J. J., Atherton, C. S., Bellouin, N., Bergmann, D., Bey, I., Bian, H., Diehl, T., Forberth, G., Hess, P., Schulz, M., Shindell, D., Takemura, T., and Tan, Q.: A multimodel assessment of the influence of regional anthropogenic emission reductions on aerosol direct radiative forcing and the role of intercontinental transport, Journal of Geophysical Research: Atmospheres, 118, 700-720, 10.1029/2012JD018148, 2013.
Zanatta, M., Gysel, M., Bukowiecki, N., Müller, T., Weingartner, E., Areskoug, H., Fiebig, M., Yttri, K. E., Mihalopoulos, N., Kouvarakis, G., Beddows, D., Harrison, R. M., Cavalli, F., Putaud, J. P., Spindler, G., Wiedensohler, A., Alastuey, A., Pandolfi, M., Sellegri, K., Swietlicki, E., Jaffrezo, J. L., Baltensperger, U., and Laj, P.: A European aerosol phenomenology-5: Climatology of black carbon optical properties at 9 regional background sites across Europe, Atmospheric Environment, 145, 346-364, https://doi.org/10.1016/j.atmosenv.2016.09.035, 2016.
Zarzycki, C. M., and Bond, T. C.: How much can the vertical distribution of black carbon affect its global direct radiative forcing?, Geophysical Research Letters, 37, n/a-n/a, 10.1029/2010GL044555, 2010.
Zelinka, M. D., Andrews, T., Forster, P. M., and Taylor, K. E.: Quantifying components of aerosol-cloud-radiation interactions in climate models, Journal of Geophysical Research: Atmospheres, 119, 7599-7615, 10.1002/2014JD021710, 2014.
Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., Feng, T., Zheng, B., Lu, Z., Streets, D. G., Ni, R., Brauer, M., van Donkelaar, A., Martin, R. V., Huo, H., Liu, Z., Pan, D., Kan, H., Yan, Y., Lin, J., He, K., and Guan, D.: Transboundary health impacts of transported global air pollution and international trade, Nature, 543, 705-709, 10.1038/nature21712, 2017a.
Zhang, R., Khalizov, A. F., Pagels, J., Zhang, D., Xue, H., and McMurry, P. H.: Variability in morphology, hygroscopicity, and optical properties of soot aerosols during atmospheric processing, Proceedings of the National Academy of Sciences, 105, 10291-10296, 10.1073/pnas.0804860105, 2008.

Zhang, X., Lin, Y.-H., Surratt, J. D., and Weber, R. J.: Sources, Composition and Absorption Ångström Exponent of Light-absorbing Organic Components in Aerosol Extracts from the Los Angeles Basin, Environmental Science & Technology, 47, 3685-3693, 10.1021/es305047b, 2013.
Zhang, Y., Forrister, H., Liu, J., Dibb, J., Anderson, B., Schwarz, J. P., Perring, A. E., Jimenez, J. L., Campuzano-Jost, P., Wang, Y., Nenes, A., and Weber, R. J.: Top-of-atmosphere radiative forcing affected by brown carbon in the upper troposphere, Nature Geoscience, 10, 486, 10.1038/ngeo2960, 2017b.

CICERO is Norway's foremost institute for interdisciplinary climate research. We help to solve the climate problem and strengthen international climate cooperation by predicting and responding to society's climate challenges through research and dissemination of a high international standard.

CICERO has garnered attention for its research on the effects of manmade emissions on the climate, society's response to climate change, and the formulation of international agreements. We have played an active role in the IPCC since 1995 and eleven of our scientists contributed the IPCC's Fifth Assessment Report.

- We deliver important contributions to the design of international agreements, most notably under the UNFCCC, on topics such as burden sharing, and on how different climate gases affect the climate and emissions trading.
- We help design effective climate policies and study how different measures should be designed to reach climate goals.
- We house some of the world's foremost researchers in atmospheric chemistry and we are at the forefront in understanding how greenhouse gas emissions alter Earth's temperature.
- We help local communities and municipalities in Norway and abroad adapt to climate change and in making the green transition to a low carbon society.
- We help key stakeholders understand how they can reduce the climate footprint of food production and food waste, and the socioeconomic benefits of reducing deforestation and forest degradation.
- We have long experience in studying effective measures and strategies for sustainable energy production, feasible renewable policies and the power sector in Europe, and how a changing climate affects global energy production.
- We are the world's largest provider of second opinions on green bonds, and help international development banks, municipalities, export organisations and private companies throughout the world make green investments.
- We are an internationally recognised driving force for innovative climate communication, and are in constant dialogue about the responses to climate change with governments, civil society and private companies.

CICERO was founded by Prime Minister Syse in 1990 after initiative from his predecessor, Gro Harlem Brundtland. CICERO's Director is Kristin Halvorsen, former Finance Minister (2005-2009) and Education Minister (2009-2013). Jens Ulltveit-Moe, CEO of the industrial investment company UMOE is the chair of CICERO's Board of Directors. We are located in the Oslo Science Park, adjacent to the campus of the University of Oslo.

CICERO Center for International Climate Research
P.O. Box 1129 Blindern
N-0318 Oslo, Norway

Phone: +47 22 00 47 00
E-mail: post@cicero.oslo.no
Web: www.cicero.oslo.no