The climate impacts of current black and organic carbon emissions

Part 2: Assessment and regional perspective

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Borgar Aamaas, Marianne T. Lund, 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

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

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Abstract: Here 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.

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Contents

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.

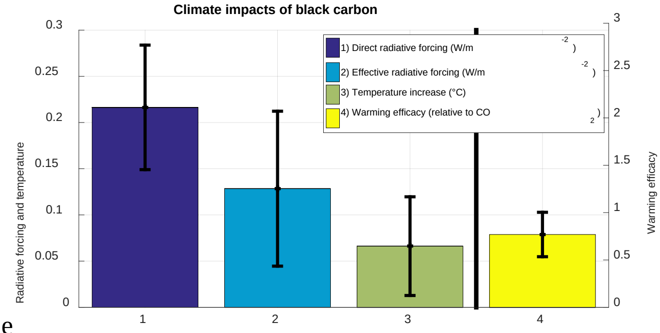


Figure 1: The current climate impacts of BC, from radiative forcing to temperature, based on results from 5 recent climate model simulations (Stjern et al., 2017). See Part 1.

In Part 1, we showed that:

- 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 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 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.

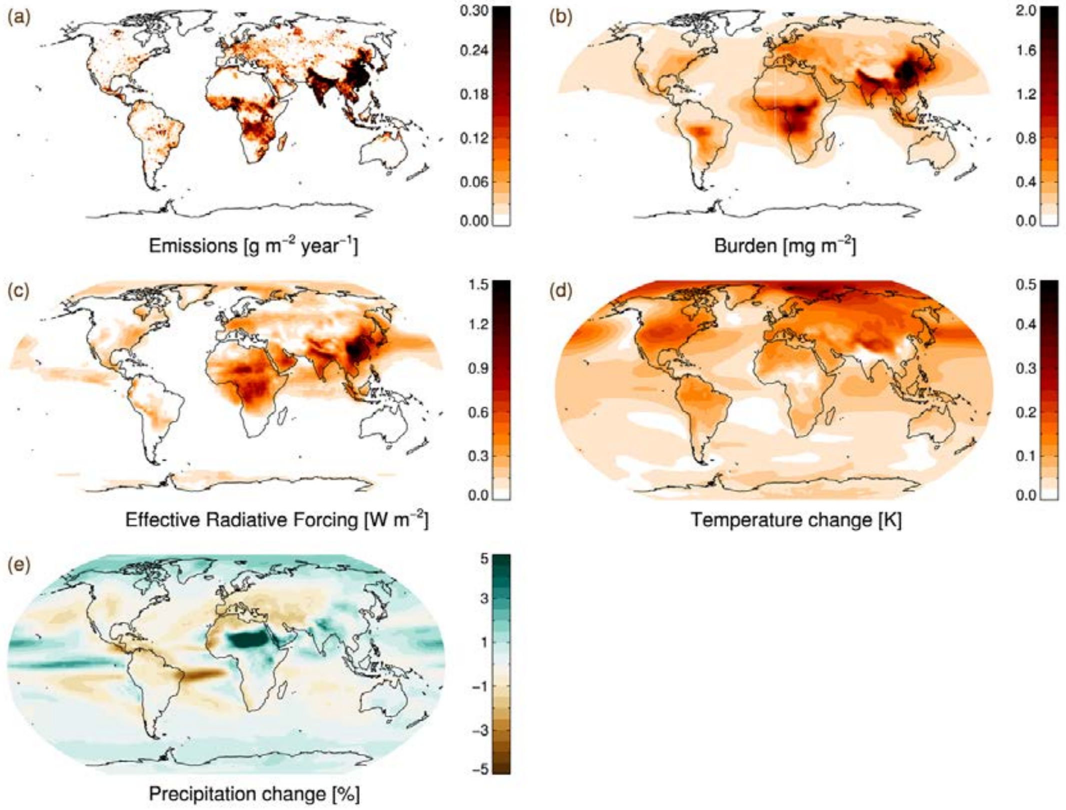


Figure 2: The cause-and-effect chain of the climate impacts of black carbon; from emissions (a), through burden (b) and radiative forcing (c), to changes in temperature (d) and precipitation (e).

2 Methodology

The path from BC and OC emissions to their climate effects goes through multiple steps. In Figure 2, we illustrate why 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., 2013)). From these locations, the particles change the energy absorption of the atmosphere i.e., radiative forcing, (panel (c) (Stjern et al., 2017)). 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., 2017); 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, 2015), 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. Also, it ensures that our temperature estimates reflect 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., 2017).
- 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 first approximation only, and dedicated studies of the climate impacts of OC undertaken in the future.

3 Regions and emissions

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).

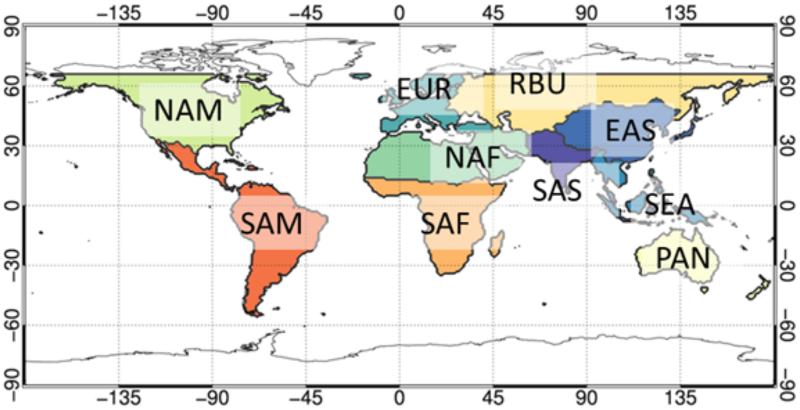


Figure 3: Emission regions used in the present assessment, consistent with those used by the HTAP collaboration (Janssens-Maenhout et al., 2015).

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.

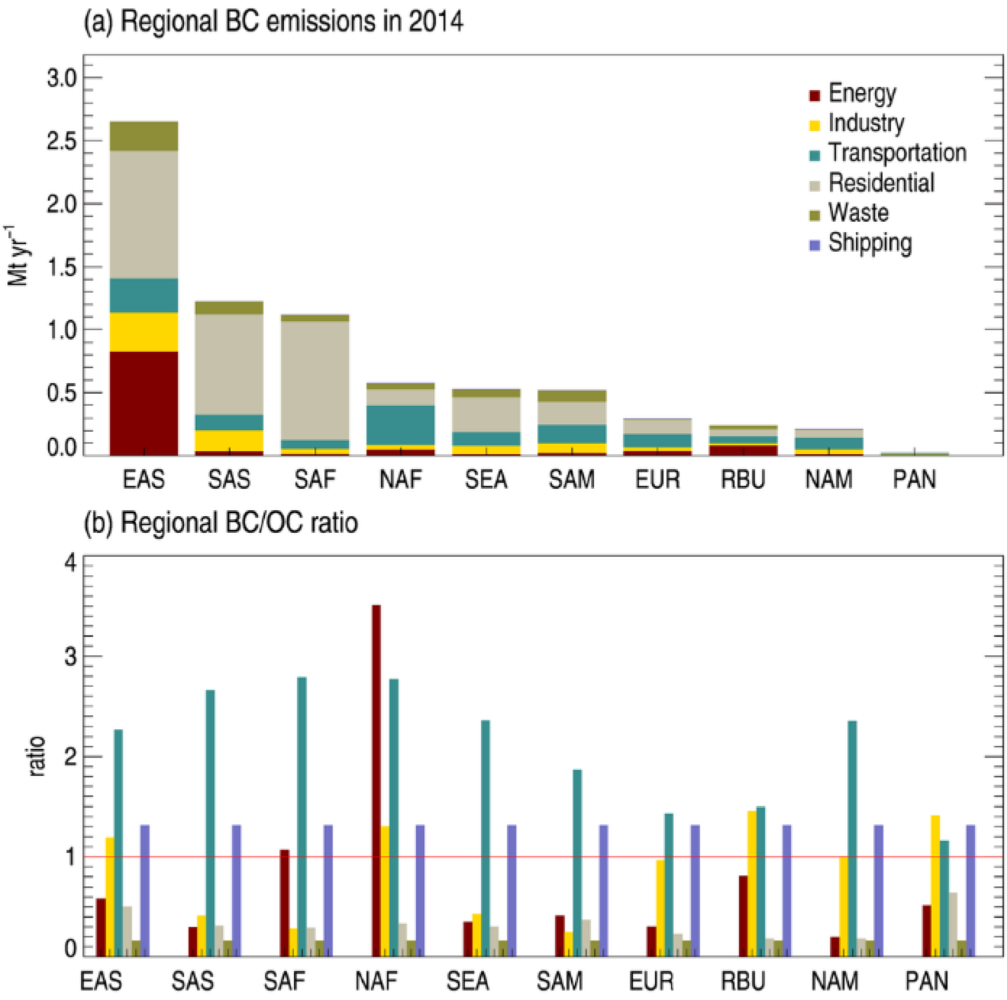


Figure 4: Regional and sectorial BC emissions (top), and the ratio of BC to OC emissions within each region and sector (bottom). Based on (Hoesly et al., 2018).

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., 2017;Baker et al., 2015), 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.

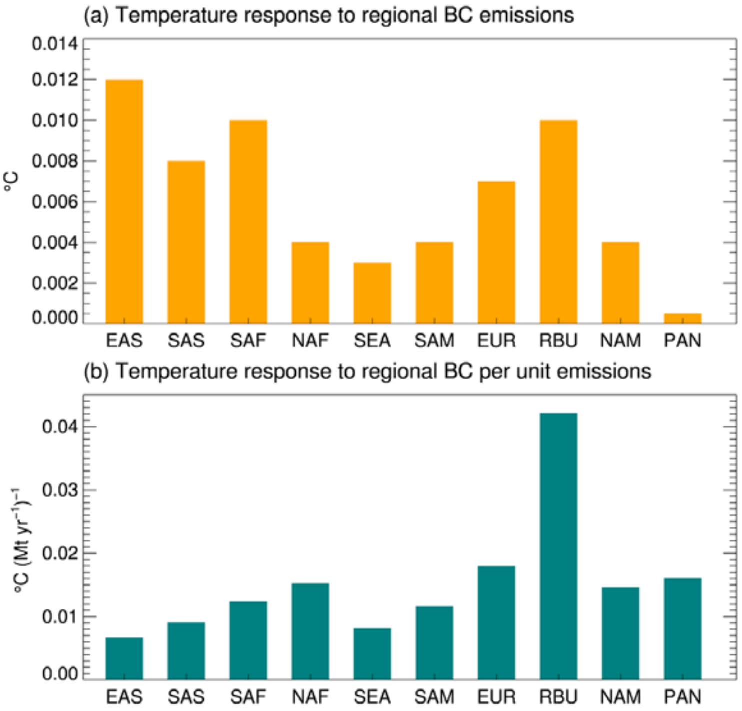


Figure 5: The global temperature effect of current (2014) regional BC emissions (top), and the global temperature change per Tg of regional emissions (bottom).

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 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 in general, because of co-emission, 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. 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.

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.

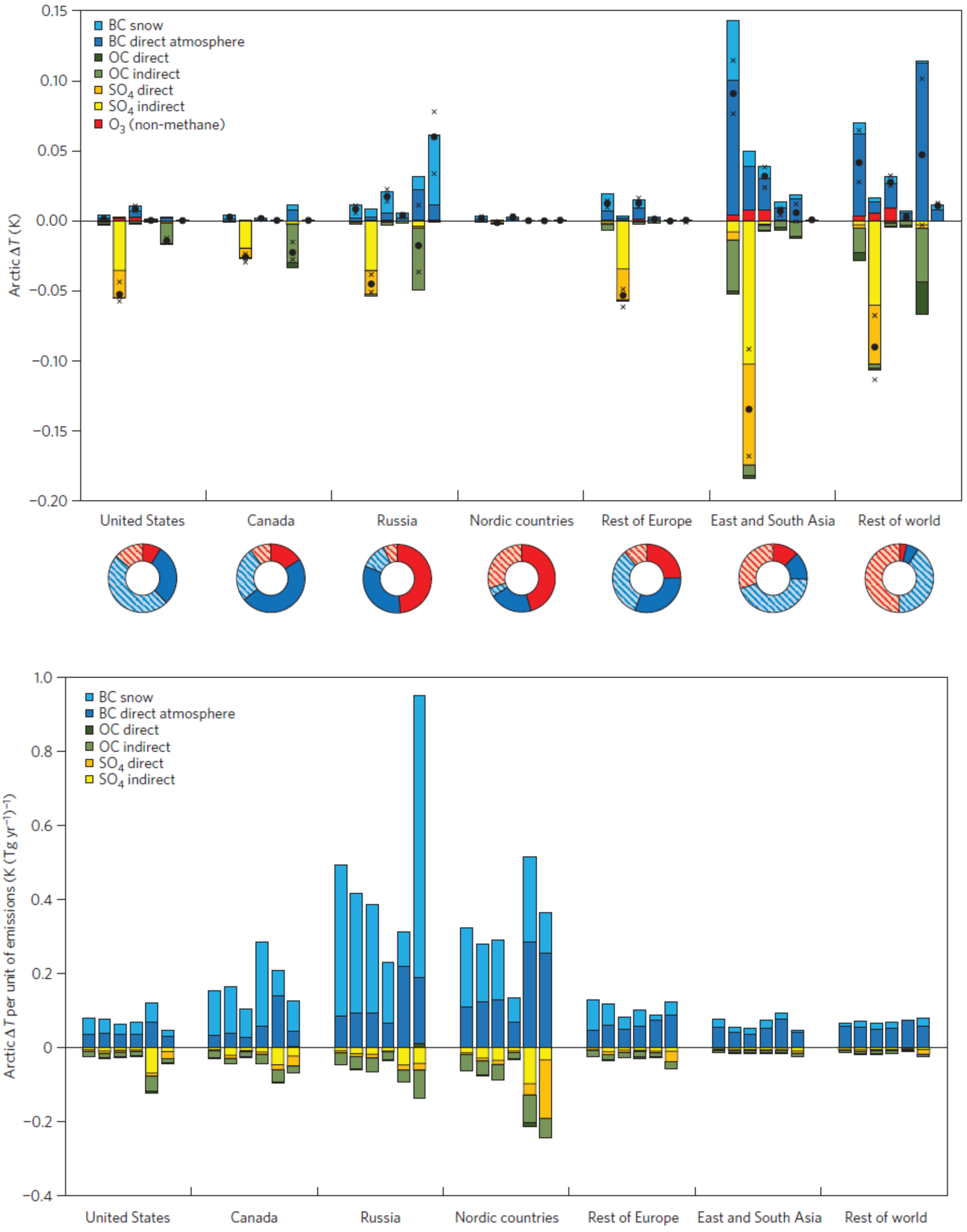


Figure 6: The influence of BC (blue), OC (green) and other short lived climate forcers on Arctic temperature. Top: Absolute changes, due to present day emissions. Bottom: Sensitivites, i.e. temperature change per million tonnes of emissions. From (Sand et al., 2016).

5.12 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 (Samset, 2018).

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., 2017;Baker et al., 2015). 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 strong 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.

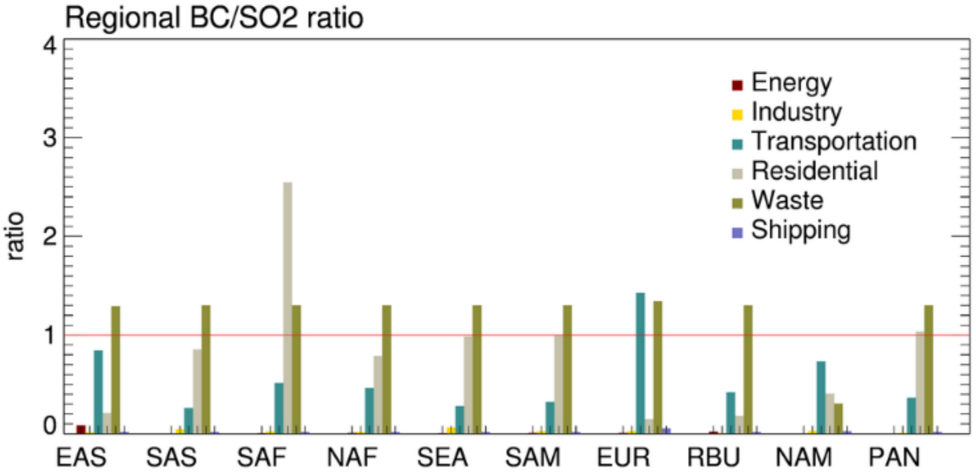


Figure 7: Ratio of BC to SO2 emissions, for the regions and sectors considered here. Based on (Hoesly et al., 2018).

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 SO2, 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. (2017)). 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

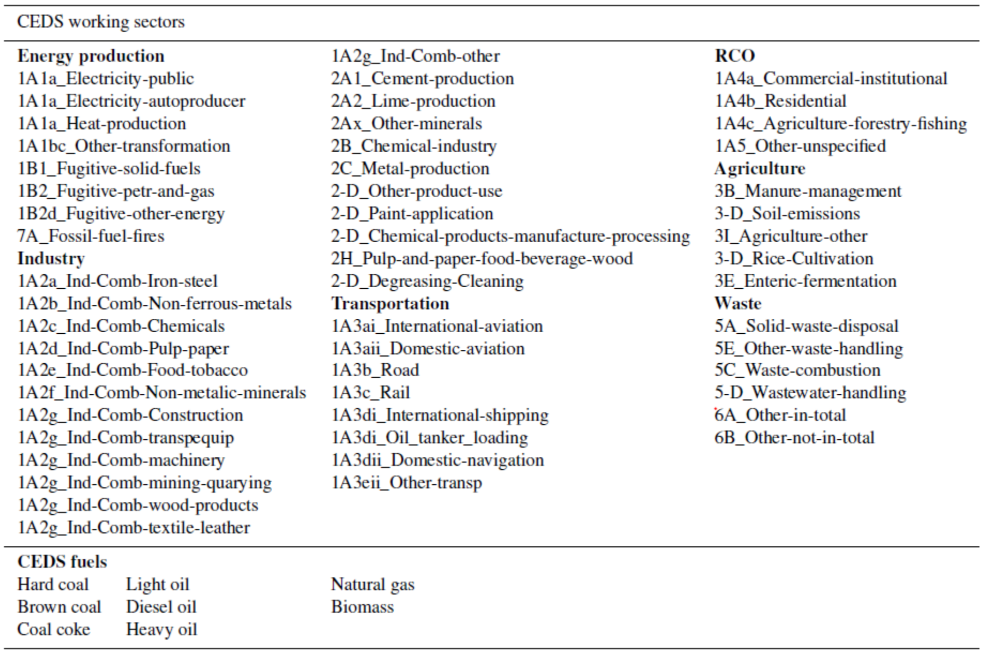
The incentives to mitigate aerosols differ substantially from the incentives to mitigate CO_2 and other long-lived components due to the shorter lifetimes of the aerosols, and the (associated) stronger local and regional climate impacts and co-benefits. Primarily due to large health co-benefits that 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. 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 SO2 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.

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
1A1a_Electricity-public
1A1a_Electricity-autoproducer
1A1a_Heat-production
1A1bc_Other-transformation
1B1_Fugitive-solid-fuels
1B2_Fugitive-petr-and-gas
1B2d_Fugitive-other-energy
7A_Fossil-fuel-fires

Industry
1A2a_Ind-Comb-Iron-steel
1A2b_Ind-Comb-Non-ferrous-metals
1A2c_Ind-Comb-Chemicals
1A2d_Ind-Comb-Pulp-paper
1A2e_Ind-Comb-Food-tobacco
1A2f_Ind-Comb-Non-metalic-minerals
1A2g_Ind-Comb-Construction
1A2g_Ind-Comb-transpequip
1A2g_Ind-Comb-machinery
1A2g_Ind-Comb-mining-quarying
1A2g_Ind-Comb-wood-products
1A2g_Ind-Comb-textile-leather
1A2g_Ind-Comb-other
2A1_Cement-production
2A2_Lime-production
2Ax_Other-minerals
2B_Chemical-industry
2C_Metal-production
2-D_Other-product-use
2-D_Paint-application
2-D_Chemical-products-manufacture-processing
2H_Pulp-and-paper-food-beverage-wood
2-D_Degreasing-Cleaning

Transportation
1A3ai_International-aviation
1A3aii_Domestic-aviation
1A3b_Road
1A3c_Rail
1A3di_International-shipping
1A3di_Oil_tanker_loading
1A3dii_Domestic-navigation
1A3eii_Other-transp

RCO
1A4a_Commercial-institutional
1A4b_Residential
1A4c_Agriculture-forestry-fishing
1A5_Other-unspecified

Agriculture
3B_Manure-management
3-D_Soil-emissions
3I_Agriculture-other
3-D_Rice-Cultivation
3E_Enteric-fermentation

Waste
5A_Solid-waste-disposal
5E_Other-waste-handling
5C_Waste-combustion
5-D_Wastewater-handling
6A_Other-in-total
6B_Other-not-in-total

CEDS fuels
Hard coal
Brown coal
Coal coke
Light oil
Diesel oil
Heavy oil
Natural gas
Biomass

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

(NB: See also the more extensive list of references in Part 1)

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.
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, 2015.
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.
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.
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.
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.
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 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.
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.
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.

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.

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, 2013.

Shilpa Rao, Zbigniew Klimont, Steven J. Smith, Rita Van Dingenen, Frank Dentener, Lex Bouwman, Keywan Riahi, Markus Amann, Benjamin Leon Bodirsky, Detlef P. van Vuuren, Lara Aleluia Reis, Katherine Calvin, Laurent Drouet, Oliver Fricko, Shinichiro Fujimori, David Gernaat, Petr Havlik, Mathijs Harmsen, Tomoko Hasegawa, Chris Heyes, Jérôme Hilaire, Gunnar Luderer, Toshihiko Masui, Elke Stehfest, Jessica Strefler, Sietske van der Sluis, Massimo Tavoni, Future air pollution in the Shared Socio-economic Pathways, Global Environmental Change, 42 (346-358), 2017

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, 2015.

Samset, B. H.: How cleaner air changes the climate, Science, 360, 10.1126/science.aat1723, 2018.

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., 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, 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, 2017.

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, 2017.