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Near- and long-term global warming of current emissions

A sectoral and regional perspective on the temperature impact from the present mix of long-lived greenhouse gas and short-lived climate forcer emissions, including a discussion of co-benefits for health, air quality and agriculture

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Abstract: Human activities influence the climate in a range of ways. While emissions of CO2 from burning of fossil fuels is the dominant factor behind the present rapid global warming, many other gases and particles also contribute. These may have short or long atmospheric lifetimes, and thus have climate impacts that are important in the near- or long-term, or both. They may also be either warming or cooling, and several climate perturbing substances may be emitted from the same sources. Consequently, determining the full impact of a given mitigation measure, aimed at reducing emissions if a given substance, is not trivial.

In the present report, commissioned by the Norwegian Ministry of Climate and Environment, we discuss the near- and long-term climate impacts of present emissions of long-lived greenhouse gases (here defined as CO2 and N2O), and a range of short-lived climate forcers. Based on this, we discuss the potential for optimal mitigation strategies across regions and sectors, including co-benefits for health and agriculture.

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Contents

Executive summary

Human activities influence the climate in a range of ways. While emissions of CO_2 from burning of fossil fuels is the dominant factor behind the present rapid global warming, many other gases and particles also contribute. These may have short or long atmospheric lifetimes, and thus have climate impacts that are important in the near- or long-term, or both. They may also be either warming or cooling, and several climate perturbing substances may be emitted from the same sources. Consequently, determining the full impact of a given mitigation measure, aimed at reducing emissions of a given substance, is not trivial.

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As future emissions are unknown, and any full estimate of the impact of a given measure therefore must rely on scenarios, we here rather focus on comparing the temperature impacts of the present mix of emissions, broken down by region and sector. We do, however, also discuss some common scenarios, and discuss the strengths and limitations of this choice for informing policy.

In summary, we find that:

- The economic sectors presently contributing most strongly to near-term surface warming, globally and regionally, are the energy, agriculture and waste management sectors. This is primarily due to their high emissions of methane.
- Black carbon (BC) contributes to warming mainly through the residential and transport sectors.
- CO_2 emissions dominate long-term warming, but also cause significant near-term warming.
- SO_2 emissions currently cause significant surface cooling. Trade-offs in terms of reduced cooling if these emissions are diminished are most pronounced in the energy, industry and shipping sectors, and in South and East Asia and the Middle East.
- East and South Asia are presently the largest sources of short-lived climate forcer emissions, including SO_2. These regions also show large cost-effective potential for mitigation of both BC and CH_4.
- There is very limited remaining cost-effective mitigation potential in the US and EU, as several efficient measures have already been implemented
- Mitigation of short-lived climate forcers does not involve co-benefit trade-offs in terms of PM2.5 or deposition of ozone, in any region studied here.

1 Introduction

Large reductions in emissions of CO_2 is key to any strategy for sustained, long-term abatement of global temperature increase. However, there is recognition within the scientific and policy communities that efforts to address climate change should also focus on actions to reduce emissions of pollutants that remain in the atmosphere for much shorter periods of time and affect climate in the near-term, so-called short-lived climate forcers (SLCFs). These include ozone, methane and aerosols and their various precursors. In particular, fulfilling the climate goals of the Paris Agreement implies strong and rapid reductions not only of CO_2, but also of methane and black carbon emissions [*CCAC*, 2018a; *IPCC*, 2018].

The short atmospheric residence time of these components implies the possibility for rapid reduction of concentrations of warming SLCFs, and hence limitation of the rate of warming. In contrast, reducing emissions of SLCFs with a cooling climate impacts, such as sulfur dioxide, which is the main precursor of sulfate aerosols, would have the opposite effect and add to the warming. Concurrently, SLCFs have significant impacts on local climate and environment, such as precipitation patterns and air quality. Hence, SLCF abatements will also have a range of co-benefits including improvements in human health and reduced damages to agriculture. The combined mitigation of CO_2 and other long-lived greenhouse gases (LLGHG) and SLCFs is therefore of key importance for reducing the near-term detrimental effects of climate change, while at the same time meeting Sustainable Development Goals (SDGs), in particular for countries where the population is vulnerable to both risk from climate change and have high exposure to air pollution.

The absolute magnitudes and relative importance of emissions of LLGHGs and SLCFs, vary between economic sectors and regions of the world. This affects the potential for near-term climate mitigation, co-benefits and potential trade-offs, which are often not taken into account in abatement discussions. Detailed knowledge of the emission mix, as well as the cost and benefits of emission reductions, is therefore crucial for the design and implementation of effective strategies for mitigation; both in the near- and long-term. However, there is no comprehensive overview available in the literature of the opportunities for reducing the warming rate inherent in combined LLGHG and SLCF mitigation. Key questions such as which SLCF emissions would be most efficient to target when co-emissions and co-benefits are taken into account, and whether the same regions and sectors give cost effective mitigation in both the near- and long-term, have been extensively discussed. As answering those questions would necessarily involve some degree of value judgement, no definitive synthesis has as yet been produced.

In response, the Ministry of Climate and Environment has asked CICERO Center for International Climate Research to provide a report discussing near- and long-term climate impacts of the present basket of emissions. Here, we compile information from recent emission inventories and model simulations, and provide an overview of the temperature impacts on different time scales from present emissions of LLGHG and SLCFs, broken down by sector and region (Section 2 and 3). The mitigation potential is then discussed in the context of cost and co-benefits of measures (Section 4 and 5). We have chosen to illustrate the near- versus long-term temperature effects of different emissions by considering the effects over time of a pulse corresponding to the present-day annual emissions. To compare the impact of SLCFs and LLGHGs over time, we use the concept of Absolute Global Temperature change Potential (AGPT) and calculate the response at different time horizons to present-day emissions (see Methods box). Comparing temperature responses at different time horizons has been recommended as a user friendly way of informing decision-makers of trade-offs between policy options targeting the long-lived versus those targeting the short-lived pollutants

[*Fesenfeld et al.*, 2018] and is a well-established framework. This methodology does not, however, directly show the effects of continuous emissions or the impact following specific scenarios for future development, which of course also is important from a mitigation perspective. To place our findings also into such a context, we discuss existing scenarios for future SLFC emissions and the implications of alternative emission pathways on temperature responses over time (Section 6).

Adopting the definitions from the IPCC Fifth Assessment report [*Myhre et al.*, 2013], we use the following terms:

- Long-lived greenhouse gases (LLGHG): Here: carbon dioxide (CO_2) and nitrous oxide (N_2O).
- Short-lived climate forcers (SLCF): Atmospheric compounds whose impact on climate occurs primarily within the first decade after their emission. Composed primarily of compounds with short atmospheric residence times compared to LLGHGs. Here: methane (CH_4), aerosols (black carbon (BC) and organic carbon (OC)) and ozone (O_3), and their precursor emissions (sulfur dioxide (SO_2), nitrogen oxide (NOx), carbon monoxide (CO) and hydrocarbons (VOC).

Methods

This report presents impacts of global, regional and sectoral emissions of SLCFs and LLGHGs on global mean surface temperature, as well as regional contributions to atmospheric fine mode particulate matter (PM2.5) concentrations and deposition of ozone to the surface, and the cost and benefits of mitigation action targeting selected emissions. We consider 13 geographical regions (Figure 2, Table 2 Appendix 1) and eight sectors (ENE: energy, IND: industry incl. solvents, RES: residential, TRA: land transport, AGR: agriculture, WST: waste management, SHP: shipping, AIR: aviation – Table 1 Appendix 1).

The PM2.5 concentration and ozone deposition due to emissions in individual regions are obtained through source-attribution analyses based on simulations with a global chemistry-transport model (OsloCTM3, *Søvde et al.* [2012]), originally performed for the Task Force on Hemispheric Transport of Air Pollution (TF HTAP) multi-model initiative [*Janssens-Maenhout et al.*, 2015].

The temperature impact of SLFCs and LLGHGs are quantified and compared using the concept of Absolute Global Temperature Change Potential (AGTP) [*Shine et al.*, 2005]. The AGTP for a species indicates the global mean temperature change at time t following 1-kg emission at t=0 (i.e., a one-time or pulse emission), and has units °C per kg. The AGTP is multiplied by the emissions in each sector/region to give the temperature impact of that emission at a given time. Here we have chosen t=10 and t=100, i.e. the impact of present-day emissions after 10 and 100 years, in order to contrast the near- and long-term effects. Using temperature responses following a pulse emission allows us to compare the impact of present-day emissions and illustrate the behavior of SLCFs and LLGHG over time. However, this method does not capture the long-term, cumulative effects of real-world emission changes or sustained emissions, for instance following mitigation implementation. The implications and interpretations of this methodological choice are discussed further in Section 7.

Regional and sectoral emissions are taken from the recent Community Emissions Data System (CEDS) inventory [*Hoesly et al.*, 2018], that will be used in the sixth IPCC assessment cycle. “Present emissions” refers to year 2014, which is the most recent available year. The exception is emissions of N_2O, which are from the Emissions Database for Global Atmospheric Research (EDGAR v4.3.2) inventory for the year 2012 [*Crippa et al.*, 2018].

Calculation of AGTPs requires an assumption on the radiative forcing of each species. For the LLGHGs we use the most recent AGTP values from the literature [*Myhre et al.*, 2013]. In the case of the SLCFs, the global temperature change per kg of emissions depends on where the emissions occur. We take this into account by calculating new, region-specific AGTPs of aerosols and the ozone precursors, NOx, CO and VOC, using the HTAP2 results (see Fig. A1). For aerosols, we account for the rapid adjustments (or semi-direct effect) of BC by adjusting its AGTP by -15% based on the current best estimates [*Stjern et al.*, 2017]. Effects of BC deposition on snow and ice are not included. To take into account the additional cooling from interactions of sulfate aerosols with clouds, we employ radiative forcing numbers from the IPCC Fifth Assessment Report, and multiply the AGTP of SO_2 by a factor of 2.10. For details about AGTP calculations, see *Aamaas et al.* [2013].

Costs, benefits and country-level incentives for mitigation actions are estimated based on methodology developed in *Aakre et al.* [2018]. Cost estimates are based on the marginal costs of abating emissions from current levels by country and industrial sector [*EPA*, 2014; *UNEP*, 2012]. In order to estimate mitigation benefits (for climate, health and crops) we use a global model of air transport and chemistry (TM5-FASST) to estimate concentrations of emitted and secondary pollutants such as ozone. We calculate gains from avoided impacts on human health and crop yields based on this model, and place a value on these benefits by using a value for protection of human life (an ethically controversial topic) and the market value of crops. We estimate the benefits from avoided climate change using the share of the global social cost of carbon that is appropriable to each country [*Nordhaus*, 2015], using a Social Cost of Carbon of USD 265 per ton carbon, and the GWP100 metric.

2 Sectoral perspective on the potential for mitigation of near- and long-term temperature change

In this section we discuss which economic sectors hold the largest potential for mitigating near- and long-term global temperature change, given present day emissions of short-lived climate forcers and long-lived greenhouse gases simultaneously. We also cover potential trade-offs due to co-emissions of warming and cooling compounds.

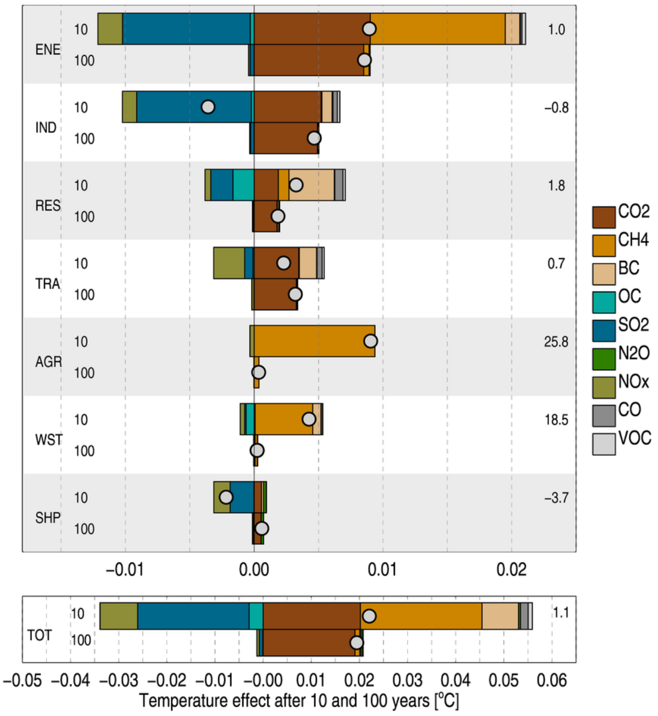


Figure 1: Global mean temperature response by sector and component 10 and 100 years following one year of present-day emissions.

Figure 1 shows the global mean surface temperature change after 10 and 100 years, following one year of present-day (year 2014) emissions. Colored bars show the temperature impact from individual species, while the circles indicate the net response (i.e. the sum of the species contributions). The lowermost panel gives the total impact of all present day emissions (TOT), while the upper panel shows the contribution from the main global economic sectors, as defined in the Appendix (Table A1). Note that the two panels are not directly comparable, due to the different values on the x-axes.

On long (100 year) time scales, CO_2 from aggregate emissions from all sectors (TOT) dominates the warming. This is as expected due to the long-lived atmospheric lifetime of these species. Note, however, that CO_2 not only gives a long-term warming, but also contributes a significant warming influence in the near-term. For total aggregate emissions, CO_2 and CH_4 impose similar impacts on the near-term warming (10 years). There is also a notable near-term warming contribution from BC, while SO_2 and NOx induce a cooling that nearly offsets the combined near-term warming from CO_2 and methane emissions.

We note, however, that NOx is particularly complicated in these types of calculations because emissions cause compensating cooling and warming impacts with different temporal behavior. In addition to increased ozone production, NOx emissions also result in a destruction of methane on intermediate timescales, which gives a cooling effect [*Wild et al.*, 2001]. The net effect is a temperature response that is initially strongly positive due to increased ozone, but decays quickly as methane destruction begin. Already after 10 years the net impact is a cooling, as seen in Figure 1. Adopting a shorter time horizon or looking at the temperature response to sustained emissions will give a different net impact that can also be warming.

The numbers on the right side of Figure 1 show the ratio of the net temperature impact after 10 years to that after 100 years. In the following, we will refer to this as the *timescale ratio*. The timescale ratio gives an indication of the relative importance of SLCF and LLGHG to the near-term temperature impact. A high number means that the near-term warming is large compared to the long-term warming, and suggests a higher added rapid abatement potential from SLCF mitigation in these sectors than in sectors with values closer to or below one. Values close to or below one on the other hand, indicate low additional potential for limiting near-term warming by targeting SLCF, either because the SLCF give small contributions compared to LLGHG or because there is a strong cooling contribution compared to warming by SLCFs. Note, however, that in the latter case measures may still be important for air quality reasons, or hold other benefits.

For total global emissions, the net temperature response in the near-term is similar in magnitude to the net response after 100 years (i.e., the timescale ratio of 1.1).This suggests that while there is potential for limiting warming in the near-term by targeting BC and methane, a strategy where also SO_2 and NOx emissions decline result in little net abatement. This emphasizes the need to simultaneously reduce CO_2 emissions.

Looking at individual sectors, much of the near-term warming comes from the agriculture (AGR) and waste (WST) sectors, for which the timescale ratio is around 20. In these sectors, CH_4 dominates, and there is little or no cooling contribution. AGR gives the highest net near-term warming of the sectors considered here. Hence, there is much to gain for near-term warming by targeting CH_4 emissions. However, because CO_2 emissions from these sectors are low, current annual emissions induce a much weaker long-term warming than the energy, industry, residential and transport sectors. Note that this result does not imply that there is no long-term reason to reduce emissions from the AGR and WST sectors. For sustained emissions, e.g. continued CH_4 emissions from the WST sector, the near-term warming we show would be present 10 years after each year of emissions, adding up to a sustained elevation of global mean surface temperature.

The largest individual contribution to warming from the global industrial sector (IND) comes from CO_2. However, emissions of SO_2 are also high, resulting in a net cooling temperature response after 10 years. If mitigation measures targeting IND CO_2 emissions also affect emissions of SO_2, the result may be a reduction of both warming and cooling in the near-term and hence little net abatement – as indicated by the negative timescale ratio. This illustrates the importance of considering co-emitted species when designing policy measures. Nevertheless, reducing CO_2 emissions is still key to limit the long-term warming of the sector.

The net near-term temperature response of present shipping (SHP) emissions is also negative. This estimate is critically dependent on the interaction of sulfate aerosols with clouds. Several studies suggest a stronger indirect effect of SO_2 emissions than accounted for by our simplified approach of scaling by a fixed factor (see Methods) and hence an even stronger cooling impact. However, there are significant uncertainties associated with this effect. On longer time scales, the net impact switches to positive as CO_2 becomes the dominating component, as also shown in previous studies [*Fuglestvedt et al.*, 2009]. The International Maritime Organization has adopted a sulfur content limit of 0.5% for shipping fuels from 2020 [*IMO*, 2016], which means that SO_2 emissions will decline and the sector may become a net warming contribution even sooner. This in turn means that effective mitigation measures for CO_2 emissions are now key for reducing the sector's climate impact.

For the energy (ENE) sector, a strong cooling impact from SO_2 is seen in the near-term. Here, however, the cooling from SO_2 is balanced by a similarly strong warming from CO_2, and an even stronger warming effect from CH_4, in addition to smaller contributions from warming impacts from BC and N_2O.

Near-term warming from BC is most pronounced in the residential (RES) and transport (TRA) sectors, adding to the warming by CO_2. In the case of residential emissions, we calculate a timescale ratio of 1.8, illustrating a potential for additional abatement of near-term warming from SLFC mitigation. In these as well as in the ENE sectors, CO_2 plays an important role on both time scales and reducing both near- and long-term temperature change requires a combined focus on SLFCs and LLGHG.

We do not include emissions from air travel here, but the topic has been covered in a recent study by *Lund et al.* [2017]. There it is shown that the formation of condensation trails and cirrus clouds give the largest warming contribution in the near-term. The results also illustrate both the short- and long-term impacts of CO_2: while CO_2 becomes dominant on longer timescales, it also gives a notable warming contribution already 20 years after the emission – similar to the other findings in this report.

In summary, present CO_2 emissions cause a significant near-term warming, in addition to the well-established long-term effect. The strongest contributions to near-term warming comes from methane in the energy, agriculture and waste management sectors, while BC plays an important role in the transport and residential sectors. Present SO_2 emissions, primarily from the energy and industry sectors, induce a cooling that offsets a significant portion of the near-term warming from the greenhouse gases. A combined focus on SLCF and LLGHG mitigation options may limit the rate of near-term warming and the long-term temperature response. The potential for trade-offs in terms of reduced cooling in the near-term arises if emissions of all SLCFs is reduced in the energy, industry and shipping sectors. This places an additional importance of simultaneous reductions in CO_2.

3 Regional perspective on potential for mitigation of near- and long-term temperature change

Here, we give an overview of the relative impacts of SLCFs and LLGHG when divided by source region and sector, and discuss where emission reductions may contribute most efficiently to limiting near-term warming. Regions and sectors where SLCF reductions are associated with potential trade-offs are highlighted.

Figure 2 shows the global mean temperature impact on 10 and 100 year time horizons following one year of present-day emissions of SLCFs and LLGHG in the 13 source regions defined in the upper panel. Figure 3 breaks the response down even further, into contributions from each sector within each region, on a 10 year time scale. The corresponding figure for the 100 year time horizon is found in the Appendix (Fig. A2).

Of the regions considered, East Asia (EAS) stands out with the largest net temperature impact both in the near- and long-term from present day emissions. CO_2 makes up the largest individual contribution to both near- and long-term warming, but there are significant contributions to warming on a short time scale from BC and methane. However, EAS is also a large source of SO_2, which gives a considerable cooling contribution, offsetting part of the near-term warming. Hence, if SO_2 emissions are reduced as a result of co-reductions from mitigation measures targeting other species or air quality improvements, there will be a trade-off or increase in warming in the near-term. Recent literature suggests that SO_2 emissions in China have declined strongly the past decade [*Li et al.*, 2017]. This decrease is not fully reflected in the CEDS emission inventory used in the present analysis, which could mean that the net warming is stronger than estimated here. NOx also gives a notable cooling contribution on a 10 year time scale. However, we again emphasize the complexity of the temperature response to NOx (Section 2) and note that on time scales shorter than 10 years, the NOx impact is positive (warming) due to ozone production.

South Asia (SAS) also experiences warming from BC and methane on a 10 year time horizon, but the cooling contribution of SO_2 and NOx emissions combined with lower CO_2 emissions result in a net temperature impact that is negative, and weaker than that from emissions in Europe (EUR) and North America (NAM) on both time scales. In both SAS and the Middle East (MDE), the cooling contributions from OC, NOx and SO_2 are almost identical to the warming contributions, leaving a negligible near-term net warming.

South and Central America (SAM, MCA), South East Asia (SEA) and South and North Africa (SAF, NAF) all have larger contributions to near-term warming from other compounds than CO_2 at present time, and their net warming on a 10 year time scale is around the same magnitude as for EUR. In SAF, the warming from present day emissions of BC is of the same order of magnitude as that from methane. This region has also seen a strong increase in SLCF emissions over past years, and is presently the second strongest source of BC after SAS.

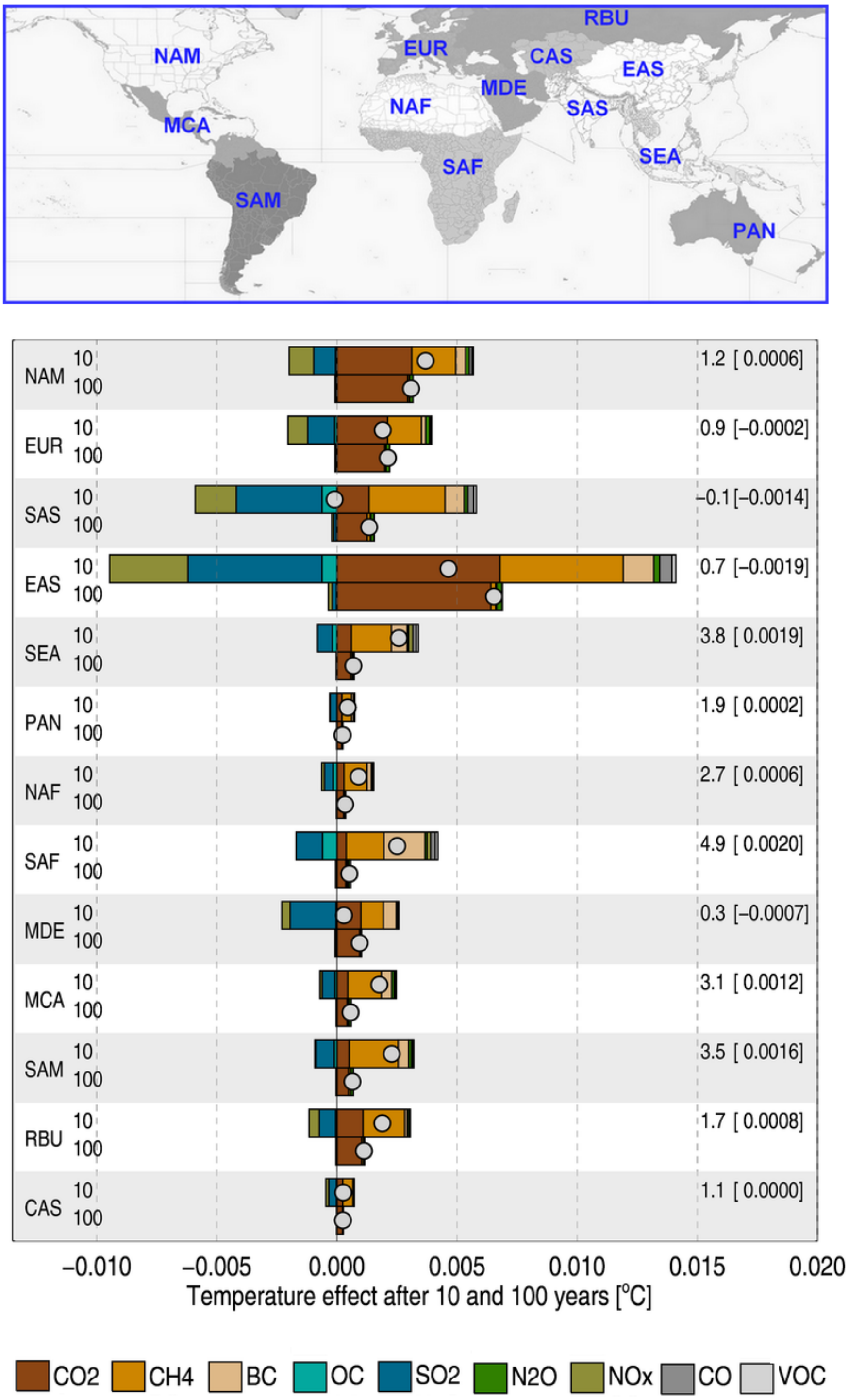


Figure 2: Upper panel shows the emission regions used in the present assessment, see also Table 2 in the Appendix. Lower panel is as Fig.1, but by region (i.e., total emissions from all sectors). The net temperature effect is shown as circles. Numbers to the right shows the ratio of near-term to long-term warming, followed by the absolute temperature difference in brackets.

In EUR and NAM, CO2 gives the largest contribution to both near- and long-term warming, but reductions in methane could be important in terms of additional abatement of near-term warming.

Because of the high present-day emissions, these regions give higher long-term warming than all other regions, except EAS.

On a 100 year time horizon, the differences between regions and sectors is determined by the difference in CO_2 (with some contribution from N_2O). We emphasize that this only captures the differences in present-day emissions. Future evolution of CO_2 (and other) emissions may follow very different pathways in the various regions and decline or increase at differing rates. The relative importance of both regions and sectors may thus change over time. Furthermore, real-world emissions will be continuous, not single years, which will affect the balance of SLCFs and LLGHG over time. In Section 6, we discuss implications of assumptions about emission in more detail and show projected regional emission development in key scenarios.

The timescale ratio is shown to the right of Figure 2. The relative importance of SLCFs in the near-term is particularly high in Africa and South America, with timescale ratios between 3 and 5. In SAS and EAS, the ratio is below 1, which primarily reflects the significant cooling contribution from SO_2. This means that reducing SLFC emissions will reduce near-term warming, but this added mitigation potential will be offset by a reduced cooling (unless only species with a warming impact can be targeted), leaving a warming due to CO_2 that is higher than the net impact of all emissions. As illustrated in Section 5, these high emitting regions contribute significantly to air quality issues. Hence, limiting near-term warming while addressing local environmental problems requires a combined focus on CO2 and SLCFs. Note that the timescale ratios do not reflect the absolute magnitude of individual regions. For instance, while the potential for additional reductions in near-term warming compared to only targeting LLGHGs is high in NAF and SAF, the net temperature impact of these regions is smaller than that from CO_2 alone in NAM and EAS.

Next, we break down regional emissions by sector (Figure 3). In many regions, the relative importance of SLFC and LLGHG in the different sectors is similar to the distribution in the corresponding sector on a global level (Figure 1). In other regions, there are important differences. The contribution to the total temperature impact from the various sectors also differs between regions. Like for the global levels (Figure 1), the agriculture and waste management sectors are dominated by warming from methane in all regions. While the energy and industry sectors are consistently the sectors responsible for the largest CO_2 emissions, they are also associated with the strongest co-emissions of cooling components. As for global total emissions, the industry sector is the only sector where the net temperature response on a 10 year time scale is negative in most regions. The most notable regional differences are found in the residential and transport sectors. For instance, BC and SO_2 make much stronger contributions to the net impact of the residential sector in South and East Asia and Africa than in northern latitude regions and South America.

In most regions, the energy sector causes the both the strongest cooling and warming temperature responses in the near-term, reflecting the high emissions from this activity. Its net impact is however not necessarily the strongest. In SAF, the strongest warming comes from the residential sector, to which BC gives the strongest contribution. In Asia and South America, the strongest warming comes from the agriculture sector.

After 100 years, CO_2 again dominates. The differences between sectors and regions, as well as the net temperature response, is mainly determined by the difference in present-day CO_2 emissions. The exception is agriculture, where N_2O now is the most important species, followed by methane which still contributes to the longer term warming. The industry sector switches from a net negative to net positive impact, and energy and industry becomes relatively more important across all regions as the cooling contribution from SO_2 decays.

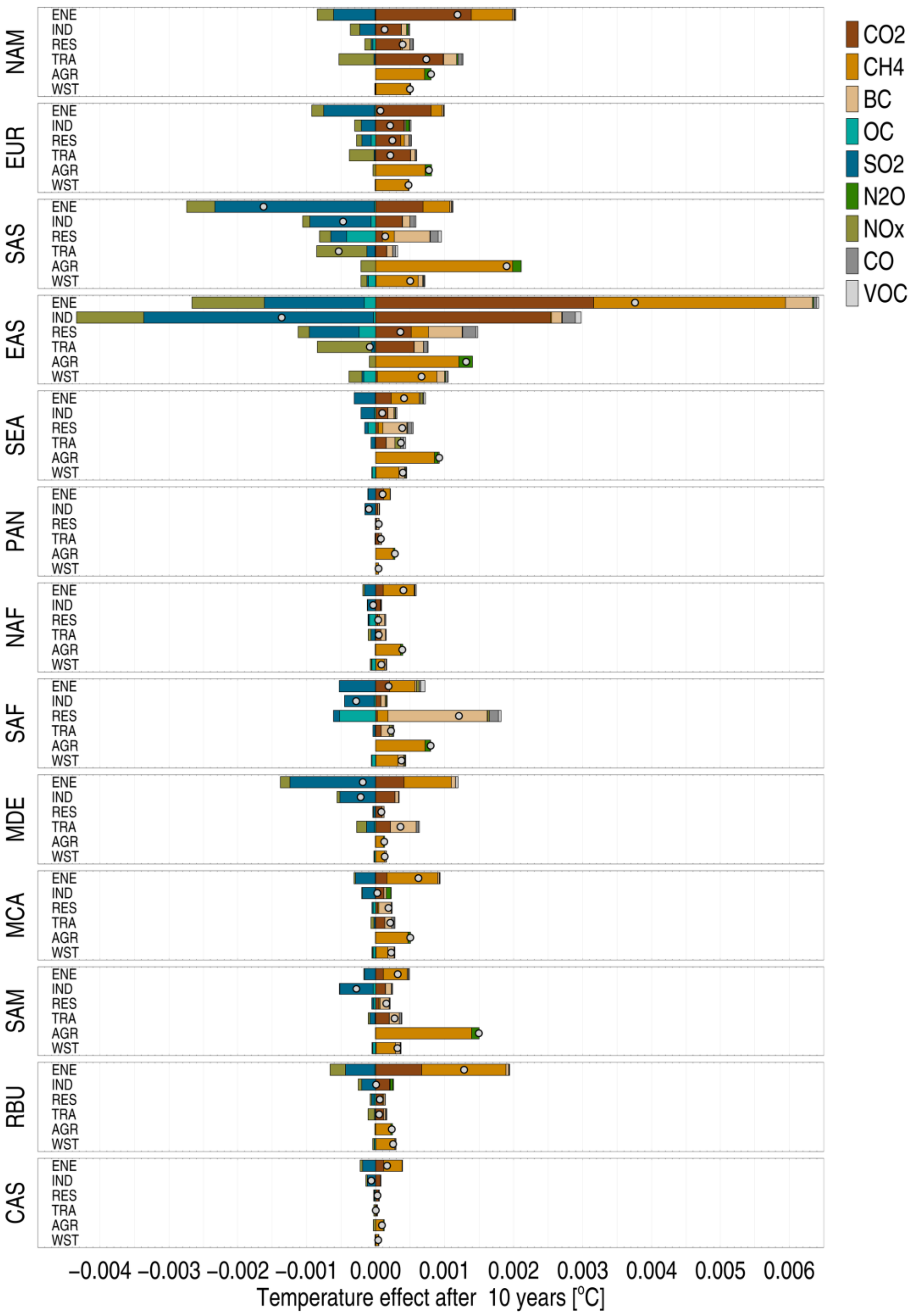


Figure 3: Temperature impact by region and species on a 10 year time scale.

In summary, if considering a mitigation strategy focusing only on SLCF, targeting emissions in Africa (predominantly BC emissions from the residential sector) and CH_4 emissions from agriculture and waste management will give a particularly efficient reduction in near-term warming, as these components make up a large portion of the warming, with limited co-emissions of cooling components. Simultaneous reductions of both SO_2 and other SLCFs in the industry sector give little warming abatement in the near-term, or even a net warming impact. Despite high SO_2 emissions, East Asia presently gives the strongest net temperature impact, with the largest individual contribution from CO_2 also in the near-term. In North America and Europe, both near- and long-term warming is dominated by CO_2.

4 Implementation of measures for mitigation of near- and long-term impacts

Here, we give an overview of incentives to mitigate emissions at the national level in key countries. Building on the results presented in Sections 2 and 3, we include assessments of specific sectorial or regional measures and costs.

Estimates of costs and benefits of mitigation actions can provide valuable information on what incentives countries may have to undertake specific actions, and thereby how likely they might be to undertake those actions. Based on previous and ongoing research we have available estimates of costs and benefits for some countries and some mitigation actions, but not at the same level of aggregation as used in Sections 2 and 3. Specifically we have estimates for the ten largest present emitters of methane and BC, for a set of six CH_4 mitigation measures and five BC mitigation measures. Our approach for estimating mitigation benefits for climate, health and crops (see Methods box), allows us to distinguish benefits accruing to the country undertaking the mitigation from benefits that accrue to other countries, as this is the basis for analyzing national level incentives to mitigate.

The ten countries considered are Australia, Brazil, China, EU, India, Indonesia, Mexico, Russia, Turkey and the USA. Compared with the 13 regions used in Sections 2 and 3 we have good coverage of North America, Europe, Russia, South Asia, East Asia and South East Asia, some coverage of Central and South America, but no coverage of the Middle East, Northern or Southern Africa.

The CH_4 measures considered target emissions from coal mining, oil and natural gas systems (production and distribution), waste (landfills and wastewater) and agriculture (rice cultivation and livestock). The BC measures include switching from traditional biomass cook stoves to stoves fueled by LPG and biogas in developing countries; replacing current residential wood burning technologies with pellet stoves and boilers in developed countries; replacing lump coal briquettes in cooking and heating stoves; introducing EURO-6/VI vehicle standards (including DPFs) for on-road and off-road vehicles.

Table 1 shows the technical potential (benefits) for each emitter, i.e. the absolute amount of BC or CH_4 that can potentially be reduced by mitigation measures, and the amount for which we find that the benefits outweigh costs at the national level. As outlined in the Methods box, the cost estimates for mitigation measures are from *EPA* [2014] and *UNEP* [2012] – note that measures that can produce a net warming are also included here. The benefits are valued using a statistical value of life of USD 3.8 million for the EU-27 in 2010, adjusted with an income elasticity of 0.8 to arrive at country specific values. For crop losses we use market values from the World Bank (average value USD 178/t). For climate benefits we use a Social Cost of Carbon of USD 265 per ton of carbon, disaggregated to country specific values using regional shares from [*Nordhaus*, 2015]. The table does not show the actual estimated costs and benefits, but rather the mitigation potential of the measures for which national benefits outweigh the costs. To aid the comparison we have highlighted values where benefits outweigh costs for more than two thirds of the technical potential in blue, and in red where this share is below one third.

	BC measures [kt BC]		**CH_4 measures [mt]**	
	Technical benefits	Benefits > costs	Technical benefits	Benefits > costs
Australia	17	6	2.3	0.9
Brazil	69	**50**	2.6	1.0
China	550	**550**	20.1	**15.1**
EU	107	**13**	8.6	**5.9**
India	650	**650**	6.0	2.8
Indonesia	183	**175**	4.0	1.5
Mexico	37	24	4.6	1.6
Russia	41	**28**	16.3	9.5
Turkey	19	**19**	1.5	0.5
USA	51	**0**	11.9	7.3

Table 1: BC (kt) and CH_4 (mt) mitigation potential and measures with a positive net value in 2030 by emitter.

One immediately striking observation is that countries would find it in their self-interest to mitigate a much larger share of BC emissions than CH_4 emissions. This finding is driven largely by the large (and geographically contained) health benefits. In the USA and EU this potential is, however, very limited as several efficient measures have already been implemented, and the cost of the remaining mitigation potential is high.

Looking across regions there is obviously a large cost-effective potential for both BC and CH_4 mitigation in Asia, and in South America (Brazil) for BC. This indicates that there may be some particularly attractive mitigation options in these regions. Note, however, that we have no data for the Middle East or Africa, and there might therefore be a very significant potential that is not included in this brief analysis.

5 Air quality co-benefits

In this section we take a closer look at the impact of regional emissions on air quality, and discuss which regions and sections could have the largest co-benefits from SLCF mitigation.

	PM2.5 [mg m^{-2}]	Total O_3 dep. [Tg/yr]	O_3 dep. near crops [Tg/yr]
NAM	0.28	42	5.1
EUR	0.20	23	2.8
SAS	0.62	40	11.6
EAS	0.74	56	6.4
SEA	0.18	22	2.8
PAN	0.06	7	0.3
NAF	0.07	8	1.0
SAF	0.31	22	2.9
MDE	0.20	18	2.2
MCA	0.08	16	0.8
SAM	0.12	20	2.2
RBU	0.10	13	1.7
CAS	0.06	22	2.8

Table 2: Influence of regional emissions on total PM2.5 and ozone deposition. The second column shows total ozone deposition, while the third column shows the deposition onto areas with crops only.

According to the World Health Organization (WHO), air pollution is responsible for several million cases of premature death each year [*WHO*, 2016]. Both airborne particles and ozone are associated with increased risk of mortality [*Fann et al.*, 2012], but small-sized particulate matter is deemed particularly health threatening as they are associated with cardiovascular and respiratory diseases [*Lu et al.*, 2015]. Meanwhile, pollution, and especially ozone, has also been shown to damage crops [*Emberson et al.*, 2018]. For instance, *Avnery et al.* [2011] estimate that global crops of wheat are reduced by up to 15 % due to the detrimental influence of ozone. This implies that reducing emissions of these short-lived components will have positive co-benefits for society in addition to the impacts on global and regional climate. In particular, improving air quality is linked to several of the UN Sustainable Development Goals (zero hunger, good health and wellbeing).

Detailed calculations of mortality and agricultural damages are beyond the scope of this report. However, to provide a first order indication and compare regions, we quantify the regional contributions to atmospheric concentrations of fine mode particles (PM2.5) and deposition of ozone to the surface, and assume these to be reasonable proxies for air quality related mortality and agricultural impacts. The results are summarized in Table 2, for emissions in each of the 13 regions, as total PM2.5 (first column), total deposition of ozone (middle column) and deposition of ozone on crops (third column). Note that these numbers do not include ozone changes due to methane emissions, only the precursors NOx/CO/VOC.

We see that emissions in East and South Asia (EAS, SAS) have by far the highest impact on global mean PM2.5 levels, followed by South Africa (SAF). These are the regions that show the largest temperature contributions from BC in Fig. , mostly due to emissions from the residential sector. Emission mitigation in these regions focusing on the residential sector, therefore, could be particularly beneficial in terms of improved air quality. A significant fraction of total PM2.5 is made up of sulfate aerosols, stemming from SO_2 emissions. This also emphasizes the need to reduce these emissions, despite the penalty on near-term temperature response due to reduced cooling. We note that high PM2.5 levels do not necessarily imply large impacts on human health as this depends on the exposure and vulnerability. However, due to the short-lived nature of the aerosols, the highest levels are generally found close to the emission sources, which in turn typically correspond to populated areas.

Total ozone depositions (second column of Table 2) are highest due to emissions in East Asia (EAS) followed by North America (NAM) and South Asia (SAS), corresponding to the high emissions of precursors (NOx, CO and VOC). However, as South Asia has the highest percentage of cropland of all the regions considered, the highest ozone deposition over cropland is found for this region. Emissions from East Asia cause the second highest deposition on crops, followed by North America (NAM). Again, we emphasize that this is only an indicator and that ozone deposition does not translate linearly into vegetation damages or reduced yields.

East and South Asia stand out as regions with high potential for health, air quality and agricultural co-benefits associated with mitigations of SLCF. There are large emissions of BC from the residential (RES) sector in the East and South Asia (EAS, SAS) regions (Fig. 3), and although there are considerable co-emissions of particularly OC (which has a cooling effect) from this sector, the total temperature impact is still a strong warming. Thus, abatements within this sector would contribute to limiting both the warming, the detrimental health impacts of small-sized particles, and well as the damages to crops.

6 Future scenarios of SLCF emissions

Here, we give a brief overview of present day emissions, and of projected changes in the level and geographical distribution of emissions under varying assumptions about policy implementation.

Up to this point, the analyses and results presented show the impacts of present-day emissions; that is, a single pulse, with no consideration of future emission development. This approach is useful for comparing SLFCs and LLGHG across emission sources and understanding their temporal behavior. However, real world emissions are continuous, and the actual impacts on global temperature can be thought of as the sum of the effects of a series of such annual emission pulses. To fully assess the impacts from a given sector region over time, some scenario for future emissions must therefore be assumed. As examples, emissions may continue at the present-day level, initially increase before being reduced, or gradually decline and level off following mitigation implementation. For instance, Aamaas et al. [2016] calculated the temperature effects following a scenario where mitigation are gradually phased in over 15 years, followed by a sustained level of reduced emissions. This approach was used in to study measures targeting SLCFs in Latin America [CCAC, 2018b].

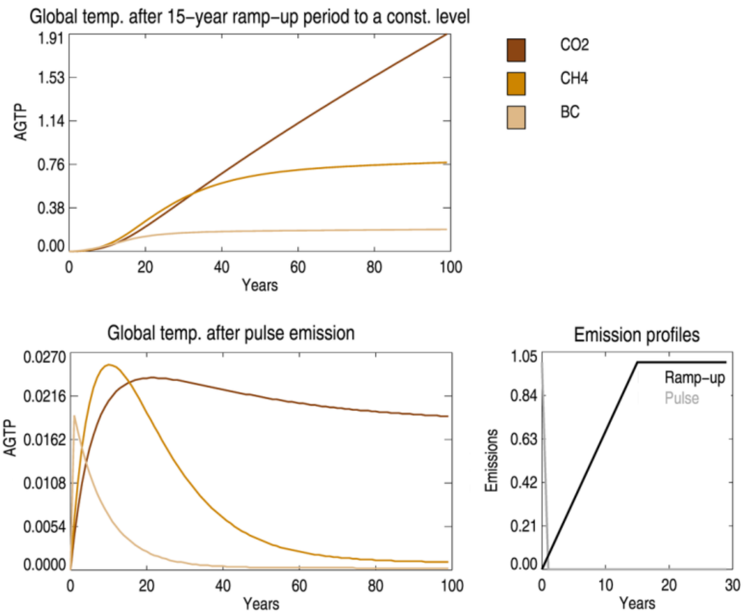


Figure 4: The temperature impact over time for BC, CO_2 and methane under two highly idealized scenarios. Small panel with grey and black lines show pulse (grey) versus gradually ramped (black) emissions. Lower panel shows the time evolution of the temperature impact of a pulse emission. The main results of this report correspond to the 10 and 100 year values of such calculations. Upper panel shows the temperature evolution from gradually ramped emissions. These curves can be thought of as the sum of a number of the time evolutions in the middle panel, stemming again from a series of pulses as shown in the left panel.

To illustrate differences between pulse and sustained emissions, Figure 4 shows the temperature impact over time for BC, CO_2 and methane under two highly idealized scenarios; a pulse (as used so far in the report) and a case of gradually increased (ramped) emissions. We select these three species due to their distinctly different temporal behavior, but other aerosols have a similar response to that of BC, while long-lived species like N_2O resemble CO_2. Under ramped and then continuous emissions (right panel), the warming from BC increases initially and is then sustained at a semi-fixed level. A similar behavior in seen in the temperature response to methane, while the impact of CO_2 continues to increase even after emissions have levelled off. Note that after 100 years the warming from methane is around 40% of that due to CO_2 in the ramped emission case, but only 5% in the pulse case. This shows the importance of methane on long-time scales for given emission pathways, as discussed in Section 2. The figure also illustrates the implications of choosing given time horizons over others. For instance, choosing 10 years as in this report to represent “near-term” means that a significant part of the initial warming from a pulse emission of a short-lived species such as BC has already disappeared, while with a shorter time horizon the full impact of methane has not been realized.

Note that while a ramped scenario is illustrative of the impact of changing emissions, it is still not representative of the complex real-word emission development – historically or into the future. For instance, according to the most recent data, global SO_2 emissions have declined over the past decades, while other SLCFs have continued to increase [*Hoesly et al.*, 2018]. Moreover, this development has differed substantially between regions. In particular, there has been a distinct geographical shift in emission of aerosols and precursors gases over the past decades, from North America, Europe, and the Former Soviet Union to Asia. After year 2000, there has also been a particularly steep rate of increase in emissions in Africa.

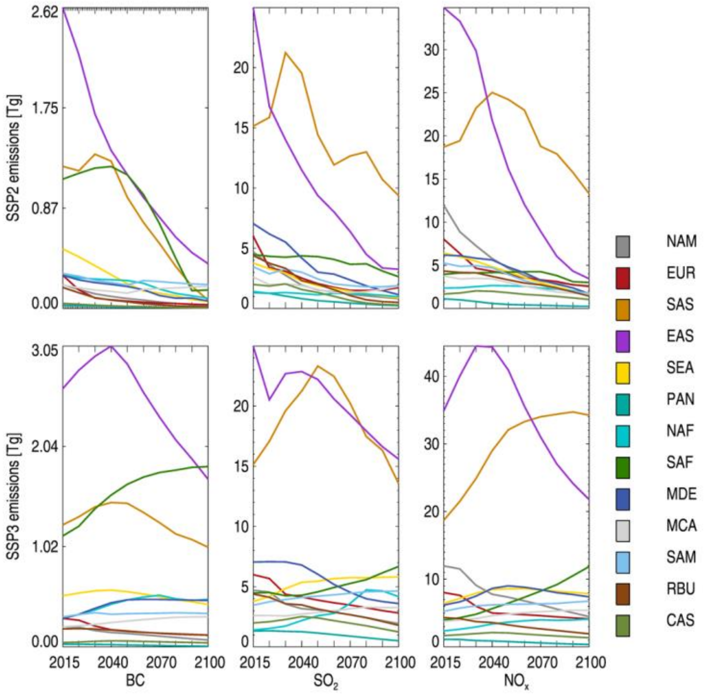


Figure 5: Emissions of BC, SO_2 and NO_x in all regions, for the emission scenarios SSP2 (upper row) and scenario SSP3 (bottom row), for years 2015 to 2100.

Similarly, the future distribution may change so that mitigation efforts may need to be focused on other regions than today. Scenarios developed in the ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) project suggest that with current legislation levels and no further control, global SLCF emissions are expected to increase [*Stohl et al.*, 2015]. A scenario where only SLCF mitigation measures with a net warming impact are targeted was found to result in strong reductions in BC and methane, but increases in SO_2 and NOx, to more than present-day levels after a temporary decline. Additional assessments of how the future levels and distributions of emissions might look are also available through the Shared Socioeconomic Pathways (SSPs) [*O'Neill et al.*, 2017], which describe plausible alternative trends in the evolution of social, economic and environmental development. Three main assumptions about future pollution controls are made: Strong, medium and weak. Strong assumes that air pollution targets are substantially tighter than today due to increasing health and environmental concerns, whereas medium follows current trends, and weak assumes regionally delayed implementation [*Rao et al.*, 2017].

Globally, emissions of all SLFCs except methane are projected to decrease towards the end of the century in all SSPs. How much and how fast, however, differ between scenarios and species. The strongest reductions are projected for SO_2 and NOx, whereas BC does not decline as much. Weak pollution control delays the start of reductions to well into the middle of the century. But the trends also differ regionally. As an example, we show in Figure 5 the emissions of BC, SO_2 and NO_x for all regions and how they evolve with time from 2015 to 2100 in two of the scenarios (SSP2 and SSP3). We have chosen these components as illustrations because they show strong regional variation in SLCF emissions between scenarios, while components such as CH_4 and CO_2 vary less. In SSP2, there is sustainable development and technological change directed toward low carbon energy sources, while in SSP3 there is still moderate economic growth but a slow technological change in the energy sector, which combined with rapid population growth makes mitigation difficult [*O'Neill et al.*, 2014]. Furthermore, these two scenarios assume strong and weak air pollution control, respectively. This difference manifests for instance as an immediate and strong reduction of BC, SO_2 and NO_x emissions in East Asia (EAS) in SSP2 (upper row, Fig. 5), but a continued increase until 2040, followed by somewhat weaker decreases in SSP3 (bottom row, Fig. 5). Other important differences are the strong increase in SO_2 emissions from North and South Africa (NAF, SAF) in SSP3, contrasting steady reductions in SSP2. In both scenarios and for all species, emissions in South Asia (SAS) continue to increase at least towards the middle of the century. These differences underline the need for continued assessments of where to focus mitigation efforts, as the current distribution of emissions may change in a number of possible ways in the future.

In summary, there is no single clear indication of how SLCF emissions will develop over time. The future evolution of aerosols and ozone precursors depends strongly on the level of air pollution control. In general, additional controls beyond the current level are needed to achieve deep cuts. In several regions, most notably in South Asia and Africa, emissions are expected to increase, at least towards mid-century, even in a scenario with strong air pollution control assumptions. BC emissions are projected to decline less than SO_2 and NOx, whereas methane emissions increase in several scenarios, pointing to a need for further, stronger mitigation strategies.

7 Discussion

In this report, we have made use of available emission inventories and methodologies for approximating the impact of emissions on climate and air quality, with a focus on comparing short and long time scale temperature effects. While all steps in the chain of logic are taken from published literature, there are naturally uncertainties inherent in the method – and in combining estimates the way we have done. Here, we briefly discuss some sources of uncertainty and the limits of present knowledge.

Our estimates do not cite explicit uncertainties or confidence intervals. Such formal analyses have been performed in some previous, rigorous studies. There are limited estimates of uncertainties in the global temperature impact of emissions from specific sectors or regions, but some examples exist. For instance, uncertainty in the temperature response to aviation emissions was estimated to be in the range35 to 65%, depending on source region and time horizon, by *Lund et al.* [2017]. Similar order of magnitude uncertainties in the temperature response to global emissions from the transport sectors was estimated by *Berntsen and Fuglestvedt* [2008]. A number of studies estimate uncertainties in the AGTP of various components. *Joos et al.* [2013] report uncertainty range of ±45% for the AGTP of CO_2, while significant ranges also exist for SLCFs [e.g., *Aamaas et al.*, 2016; *Collins et al.*, 2013; *Fuglestvedt et al.*, 2010] Factors that contribute to these ranges include uncertainties in the emission inventories and their underlying methodology, incomplete knowledge of transport and atmospheric chemistry related to the SLCFs, differences between estimates of the temperature impact of a given climate perturbation, and the climate sensitivity assumed in the analysis.

For the comparison across different emission sources in present analysis, the climate sensitivity (i.e. the temperature response of the climate system to a hypothetical doubling of CO_2) is not a critical factor. The metrics used here assume a global warming of around 3 °C for a doubling of the CO_2 concentration, and that this does not depend on region or sector. Hence, while a change in sensitivity will affect the absolute temperature change values given, it will not significantly affect the relative mitigation potentials or timescale ratios we report.

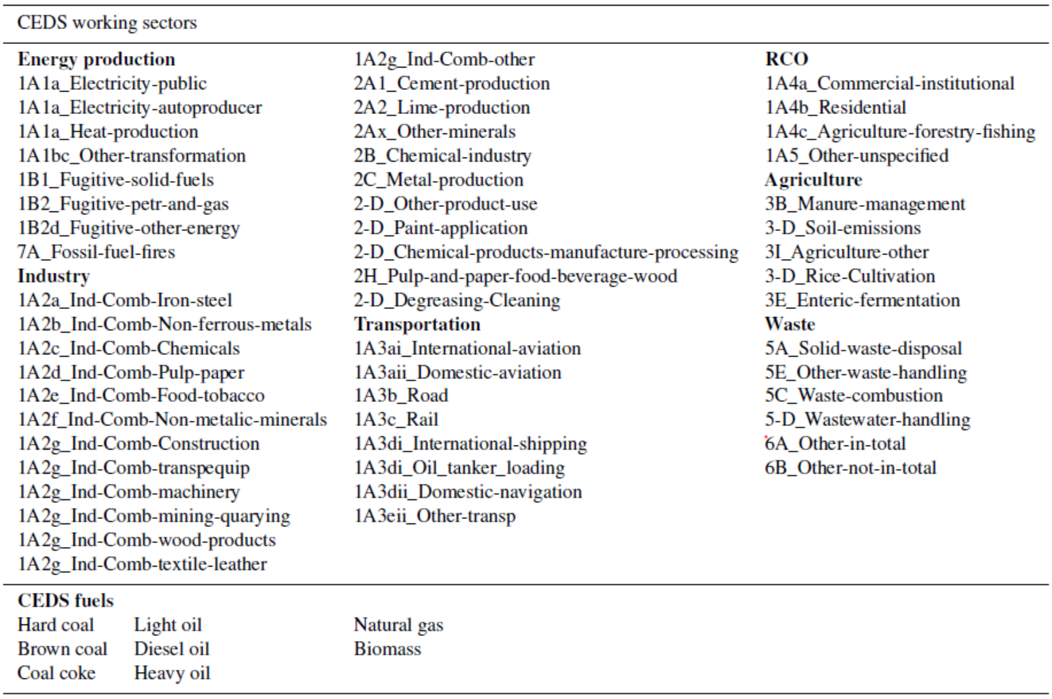
Other parts of the analysis, such as the scaling factors used to take into account the indirect effect of SO_2 and semi-direct effect of BC, the precise values of the AGTP metric values, and the chosen social cost of carbon, are still subject to active scientific debate. Consequently, we have attempted to choose representative values, but not attempted to perform an assessment of the present literature. Overall, we are confident that our estimates are consistent with recent literature, but we also note that updates may be required as research progresses.

In this report we have chosen to use temperature response as the indicator of the climate change imposed by emissions, and to not present numbers in terms of CO_2-equivalence, i.e., the impact of a given species normalized by the impact of CO_2. We note, however, that there are other metrics and approaches for comparison the impacts of various emissions on different time scales, with corresponding advantages and disadvantages [*Fuglestvedt et al.*, 2010]. The most common emission metric, and the one used in e.g., national emission reporting and emissions trading, is the Global Warming Potential (GWP). There is ongoing discussion about the use of GWP for SLCFs, in particular methane, in a regime where emissions drop rather than continually increase. Recent literature suggests using a metric called GWP* rather than the established values, to take into account the fact that most of the climate impact of SLCF emissions occurs over the first years and decades after emission [*Allen et al.*, 2018]. We have not taken the GWP* discussion into account here, but note that it could alter the relative importance of new versus established sources of methane emissions.

In conclusion, while our method is subject to significant uncertainties, it is our assessment that the relative temperature impacts and time scale ratios cited above are robust and consistent with the present state of knowledge.

Appendix

Table A1: 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.)

Table A2: Description of regions used in this report, consistent with those used by the Hemispheric Transport of Air Pollution (HTAP) collaboration [*Janssens-Maenhout et al.*, 2015]. See map in Figure 2.

	Region
NAM	US+Canada (up to 66 N; polar circle)
EUR	Western + Eastern EU+Turkey (up to 66 N polar circle)
SAS	South Asia: India, Nepal, Pakistan, Afghanistan, Bangadesh, Sri Lanka
EAS	East Asia: China, Korea, Japan
SEA	South East Asia
PAN	Pacific, Australia+ New Zealand
NAF	Northern Africa+Sahara+Sahel
SAF	Sub Saharan/sub Sahel Africa
MDE	Middle East: S. Arabia, Oman, etc., Iran, Iraq
MCA	Mexico, Central America, Caribbean, Guyanas, Venezuela, Columbia
SAM	South America
RBU	Russia, Belarussia, Ukraine
CAS	Central Asia

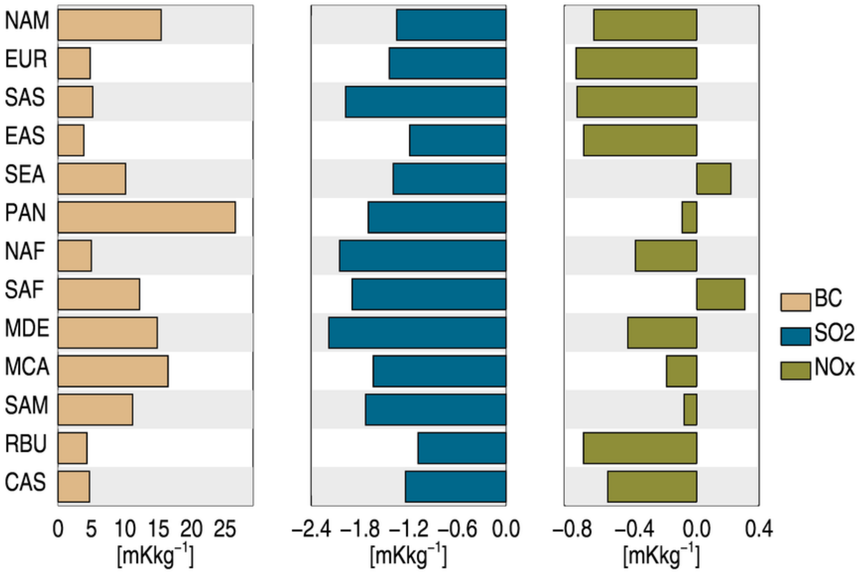


Figure A1: Regional efficiency, showing temperature influence per kg emissions of selected components, after 10 years.

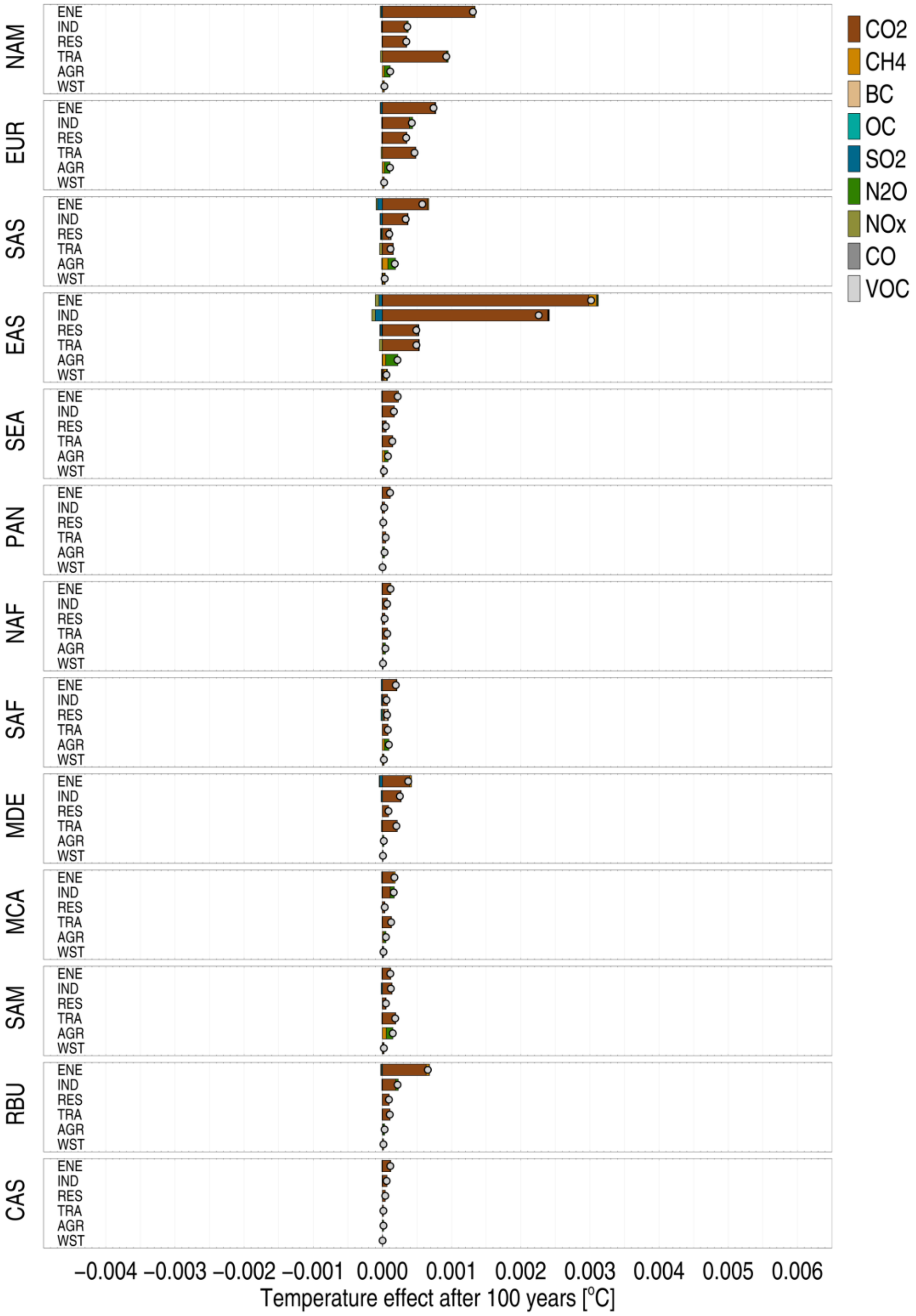


Figure A2: Temperature impact by region and species on a 100 year time scale.

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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.

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