https://doi.org/10.5194/esd-2020-9
Preprint. Discussion started: 16 March 2020

Earth System Dynamics
Discussions

A continued role of Short-Lived Climate Forcers under the Shared Socioeconomic Pathways

Marianne T. Lund[1], Borgar Aamaas[1], Camilla W. Stjern[1], Zbigniew Klimont[2], Terje K. Berntsen[1,3], Bjørn H. Samset[1]*

1 CICERO, Center for International Climate Research, Oslo, Norway

2 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

3 Department of Geosciences, University of Oslo, Oslo, Norway

**Corresponding author: m.t.lund@cicero.oslo.no*

Abstract

Mitigation of non-CO_2 emissions plays a key role in meeting the Paris Agreement ambitions and Sustainable Development Goals. Implementation of respective policies addressing these targets mainly occur at sectoral and regional levels and designing efficient mitigation strategies therefore relies on detailed knowledge about the mix of emissions from individual sources and their subsequent climate impact. Here we present a comprehensive dataset of near- and long-term global temperature responses to emissions of CO_2 and individual short-lived climate forcers (SLCFs) from 7 sectors and 13 regions - for present-day emissions and their continued evolution as projected under the Shared Socioeconomic Pathways. We demonstrate the key role of CO_2 in driving both near- and long-term warming, and restate the importance of mitigating methane emissions, from agriculture, waste management and energy productions, as the primary strategy to further limit near-term warming. Due to high current emissions of cooling SLCFs, policies targeting end-of-pipe energy sector emissions may result in net added warming unless accompanied by simultaneous methane and/or CO_2 reductions. East Asia, North America and Europe remain the largest contributors to total net warming until 2100, regardless of scenario, while South Asia and Africa south of the Sahara overtakes Europe by the end of the century in SSP3-7.0 and SSP5-8.5. We find that SLCFs will continue to play a role in many regions, particularly those including low- to medium-income countries, under most of the SSPs considered here. Our dataset is made available in an accessible format, aiming also at decision-makers, to support further studies into the implications of policy implementation at the sectoral and regional scales.

1 Introduction

At the core of any strategy for sustained, long-term abatement of climate change are strong reductions in emissions of CO_2 and other long-lived greenhouse gases (LLGHGs). However, most anthropogenic activities emit a suite of additional species, with a range of climate impacts, commonly termed short-lived climate forcers (SLCFs). While differing in characteristics and contribution to temperature change, their common feature of a much shorter atmospheric residence time compared to LLGHGs has resulted in significant discussion of the role of SLCFs in climate mitigation strategies, in particular to limit near-term warming (e.g.,Bowerman et al., 2013; Pierrehumbert, 2014; Rogelj et al., 2015; Shindell et al., 2012; Shoemaker et al., 2013; Stohl et al., 2015).

Many studies have placed particular emphasis on the subset of SLCFs with a warming impact on climate, namely black carbon (BC), methane (CH_4) and tropospheric ozone (sometimes collectively referred to as short-lived climate pollutants, or SLCPs) (e.g., AMAP, 2015; CCAC, 2019; UNEP, 2017). Assuming effective abatement of SLCPs, some studies estimate a reduction in global temperature of 0.2-0.5°C increase by mid-century (e.g., Shindell et al., 2012). Early studies brought particular attention to BC mitigation as a measure to limit near-term (rate of) warming owing to the strong positive radiative forcing combined with short atmospheric residence time of the aerosols (e.g., Ramanathan & Carmichael, 2008). More recent work suggest that some of these early estimates may overestimate the effect of SLCP mitigation (Rogelj et al., 2014; Smith & Mizrahi, 2013; Stohl et al., 2015; Takemura & Suzuki, 2019). While results from early studies brought some concern that the attractiveness of SLCP mitigation could lead to delayed action on CO_2 emissions, most scientific studies emphasize that SLCP measures should only be considered complimentary to early and stringent CO_2 mitigation for the achievement of long-term climate goals (e.g., Bowerman et al., 2013; Rogelj et al., 2014).

SLCF mitigation may also give rise to potential trade-offs. As many species are commonly co-emitted, any given mitigation measure or policy will affect a broad range of emitted components. The combinations may, however, vary significantly between mitigation strategies motivated by, and designed to address, different societal challenges. For instance, SLCFs are inexorably linked to air quality (Anenberg et al., 2012; Lelieveld et al., 2015; Shindell et al., 2012) and sustainable development (Haines et al., 2017; UNEP, 2019), in addition to their climate impacts. The numerous environmental and societal co-benefits of SLFC reductions are well recognized but may lead to adverse climatic consequences (Arneth et al., 2009). While some SLCFs with a warming contribution to temperature change can, in part, be mitigated individually (in particular methane), improving air quality requires consideration of all relevant species, not just the warming BC particles. Removal of all present-day anthropogenic aerosols may add as much as 0.5°C of additional global near-term warming according to recent work (Aamaas et al., 2019; Hienola et al., 2018; Samset et al., 2018). Due to the co-emission, species such as sulfur dioxide (SO_2) are also commonly affected by climate mitigation policies that consider LLGHGs as a primary target. Hence, while it remains clear that deep reductions in emissions of methane and BC play a key role in pathways for global emissions that limit global warming to 1.5°C and 2°C warming (Harmsen et al., 2019; Rogelj et al., 2015; Rogelj et al., 2018; Shindell & Smith, 2019; Xu & Ramanathan, 2017), any assessment of the mitigation potential by SLCF reductions should encompass species such as sulfate, which have arguably received considerably less attention so far.

A key characteristic of SLCFs is that the relative amount of SLCF emissions, as well as their subsequent radiative forcing, can vary significantly between individual emission sources (Bond et al., 2013; Lund et al., 2014b; Persad & Caldeira, 2018; Unger et al., 2010). Furthermore, while previous scenarios for long-term evolution of SLCF emissions project a general, rapid decline even in pathways with high climate forcing and GHG levels (Gidden et al., 2019; Rao et al., 2017), the most recent generation scenarios, the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014; Riahi et al., 2017) exhibit a much larger spatiotemporal heterogeneity in projected future SLCF emissions. An up-to-date and detailed consideration of the emission composition is therefore critical for the design of effective mitigation strategies and to provide decision makers with a more integrated approach and guidance on how to best address linkages between climate, sustainable development and air quality in policy processes (Melamed et al., 2016). While studies comparing and quantifying the impacts of SLCFs and CO_2 exist, they differ in selection of sectors and/or regions, methodology and emission inventory, making direct comparison difficult (e.g., Harmsen et al., 2019; Kupiainen et al., 2019; Lund et al., 2014a; Sand et al., 2015; Unger et al., 2010). Furthermore, studies often consider only the equilibrium effect of present-day emissions, emission pulses or very simplified scenarios.

In the present work, we provide a comprehensive and updated investigation of the contribution to near- and long-term global temperature impacts from individual SLCF and LLGHG emissions. We first quantify the temperature response to an idealized pulse of present-day emissions to demonstrate the methodology and temporal behavior of the various emitted species, then calculate possible future evolutions of temperature impacts as they are projected to develop under the pathways for future socioeconomic development, climate policy and air pollution described by the SSPs. The temperature impact is calculated for seven economic sectors and 13 source regions, accounting for best available knowledge and geographical dependence of the forcing efficacy of different SLCFs, thereby providing a more comprehensive overview than previous literature, focusing on both added benefits and trade-offs offered by SLCF mitigation. By making our full data set openly available, we aim to provide a toolkit for further studies of the implications of policy implementation at the sectoral and regional level and demonstrate such use through calculations of the effect a set of idealized sectoral policy packages.

2 Methodology

Using the concept of Absolute Global Temperature change Potential (AGTP) (Shine et al., 2005), we calculate the global-mean temperature response over time to emissions of CO_2, CH_4, ammonia (NH_3), BC, OC, SO_2, the ozone precursors nitrogen oxide (NOx), carbon monoxide (CO) and volatile organic compounds (VOCs) from the sectors and regions shown in Fig. 1.

The AGTP is an emission metric-based emulator of the climate response, and a well-established method that enables us to quantify and compare global temperature impacts of a large number of sources and scenarios in a transparent and, in terms of computer resources, cost-effective manner. The approach is described in detail in the literature (Aamaas et al., 2013; Fuglestvedt et al., 2010; Shine et al., 2005); here we give a brief outline.

The ATGP gives the global-mean surface temperature response per kg emitted as a function of time after an emission pulse, i.e., an instantaneous one-off emission. At time H after the emission, the AGTP for species i is given (for each sector and region) by:

$$AGTP_i(H) = \int_{t=0}^{H} F_i(t) IRF_T(H-t)dt$$

where F is the radiative efficiency and IRF is the impulse response function used to estimate the temperature response to a given radiative forcing. See Aamaas et al. (2013) for further details about AGTP calculations for individual species. For CO_2 and methane, we use the global-mean F from the IPCC Fifth Assessment report (AR5) (Myhre et al., 2013), adjusted for recent updates of the methane forcing (Etminan et al., 2016). For short-lived species (with the exception of ammonia (NH_3), for which we also use the IPCC AR5 best estimate global forcing value), we use values of F that depend on the location of the emission and calculate region-specific AGTPs for BC, OC, SO_2, and ozone precursors. These regional radiative efficiencies (i.e., the global radiative forcing per unit of regional emissions) are derived from simulations performed with the global chemistry transport model OsloCTM3 (Lund et al., 2018; Søvde et al., 2012) for the second phase of the Hemispheric Transport of Air Pollution (HTAP2) (Janssens-Maenhout et al., 2015) combined with radiative kernels. To account for the additional negative RF resulting from aerosol-cloud interactions (or indirect aerosol effects), we scale the regional AGTP of SO_2 by a factor of 2.1 based on the ratio of total global RF of sulfate to that due to direct effects alone from the IPCC AR5 (Myhre et al., 2013). Due to lack of available information, the same scaling factor is applied for all regions, recognizing that also the indirect effect may vary with location of emission. We also account for the rapid adjustments of BC which have been found to partly offset the positive direct radiative impact (Samset & Myhre, 2015; Stjern et al., 2017), by adjusting the AGTP of BC by -15% (based on Stjern et al. (2017), in all regions except South Africa, where the rapid adjustments were positive in that study. Radiative forcing of BC deposition on snow and ice is not included in our estimates.

Following the methodology established in the literature (e.g., Fuglestvedt et al., 2010), we use an IRF that is the sum to exponentials representing the short and long mode of the climate system response to a perturbation:

$$IRF(t) = \lambda \sum_{j=1}^{J} \frac{c_j}{d_j} \exp\left(-\frac{t}{d_j}\right)$$

Here, c_j and d_j are constants and timescales of the two modes, respectively, and λ is the equilibrium climate sensitivity (ECS) (Table 1). Values of c_j, d_j and λ are derived from the analytical solution of the two-layer energy balance model used by Geoffroy et al. (2013), which yields an ECS of 0.885 K $(Wm^{-2})^{-1}$). This is somewhat lower than the ECS of 1.06 K $(Wm^{-2})^{-1}$) inherent in the IRF from Boucher and Reddy (2008) which has been used in a number of previous studies including the IPCC AR5. The timescales from Geoffroy et al. (2013) are also

https://doi.org/10.5194/esd-2020-9
Preprint. Discussion started: 16 March 2020

somewhat shorter than the corresponding Boucher and Reddy (2008) numbers. Combined, this results in lower AGTPs values in the present study than previous literature.

For each region and species, the AGTPs are then multiplied by present-day (year 2014) emissions from the Community Emission Data System (CEDS) (Hoesly et al., 2018) to calculate the temperature impact at a given time horizon H, $\Delta T(H)$. In this study, H=10 years and H=100 years are selected to present near-term and long-term impacts, respectively. The AGTP framework can readily be extended from pulse-based calculations since any scenario can be viewed as a series of pulse emissions and analyzed through convolution (Aamaas et al., 2013). The temperature response ΔT at time t for species i is (for each region and sector) given by:

$$\Delta T_i(t) = \int_0^t E_i(t')AGTP_i(t-t')dt'$$

Using this approach, we also calculate the global-mean temperature response to full time series of historical (CEDS) and future (the nine gridded and harmonized SSPs (Gidden et al., 2019)) regional and sectoral emissions.

We establish a range in total net global-mean temperature response on 10- and 100-year time scales due to uncertainties in radiative forcing by performing a Monte Carlo analysis. Each RF mechanism is treated as a random variable, following a probability density function (PDF) defined based on existing literature, and the distribution for the total RF is derived by summing the individual PDFs, i.e., assuming that each RF mechanisms is independent. For the aerosols and their precursors, we use the multi-model results from the AeroCom Phase II experiment (Myhre et al., 2013a), while for CO_2 NH_3, and ozone precursors, we use the uncertainties from the IPCC AR5 (Myhre et al., 2013b). For further details, see Aamaas et al. (2019) and Lund et al. (2017). Our temperature responses are also influenced by uncertainties in emissions and climate sensitivity. A comprehensive analysis of uncertainty in all three factors is challenging due to lack of data, but the potential impact is discussed in Sect. 4.

3 Results

3.1 Near- and long-term temperature response to current emissions

We first discuss the global mean surface temperature response to one year of present-day (i.e., year 2014) emissions, for global total emissions and broken down by key contributing sectors and geographical source regions as shown in Fig.2. While the 10- and 100-year time horizons are commonly used to represent near- and long-term impacts, we recognize that other choices may affect the relative importance, and even sign, of some of SLCFs like aerosols and NOx, or be more relevant for certain applications.

Globally, current emissions result in an approximate balance between cooling and warming SLCFs in the near-term, with main warming contributions from BC and CH_4 and cooling from SO_2 and NOx (Fig.2a). As the impact of the SLCFs decays rapidly over the first few decades after emission, the net long-term temperature impact is predominantly determined by CO_2. Note that in Fig.2b-c we only show this net temperature effect (grey circles) for the 100-year time scale, not individual contributions.

As clearly seen in Fig. 2, CO_2 emissions also cause a notable contribution to near-term warming. While known in the scientific community, this role of CO_2 as both a near- and long-term climate forcer is not always fully acknowledged in the discussions of LLGHGs versus SLCFs. Figure 2 also readily shows that the mitigation potential inherent in the present SLCF emissions is highly inhomogeneous, and that co-emitted species – including CO_2 – must be taken into account in any targeted climate policy.

Differences in emission composition result in net near-term impacts on global temperature (i.e., 10 years after emission) that vary significantly, in both magnitude and sign, between sectors and regions. Of the global economic sectors, the largest net near-term warming is estimated for the energy (ENE), agriculture (AGR), and waste management (WST) sectors (Fig. 2b). The AGR and WST sectors are primarily a source of methane-induced near-term warming. The energy sector (ENE) is also characterized by a significant warming due to methane (originating from fossil fuel mining and distribution) but also by a considerable cooling from high emissions of SO_2. Our results hence reinforce the importance of methane as a driver of near-term warming but show that benefits from reductions may be offset if accompanied by simultaneous reductions in SO_2 in some cases. A particular feature of the energy sector, however, is that a significant portion of methane mitigation from oil and gas as well as coal mining (production and distribution) can be done independently from other energy-related (combustion) emissions. An explicit distinction between production and combustion emissions was not available in the gridded CEDS inventory, but, as illustrated in the following section, mitigation strategies targeting one category or the other can result in distinctly different temperature outcomes. On the global level, emissions from industry (IND) cause a small net cooling impact despite a considerable warming from CO_2 emissions. The near- and long-term temperature impacts from the aviation sector were recently quantified in a separate study (Lund et al., 2017).

Current SO_2 emissions are also the primary contributor to near-term cooling in all source regions (Fig.2c), with smaller contribution from NOx. The largest absolute contribution to net near-term warming is caused by emissions in East Asia (EAS) and North America (NAM), followed by South East Asia (SEA) and South Africa (SAF). However, the relative contributions from individual species vary. In EAS and NAM, as well as Europe (EUR), the impact of current emissions of cooling and warming SLCFs approximately balance in the near-term and these regions cause comparable net warming impacts on 10- and 100-year time scales, as seen by comparing the white and grey circles in Fig. 2c. These balancing characteristics do not imply that SLCF emission reductions measures should not be implemented, but that the net benefits on global temperature may be lower than expected if mitigation policies simultaneously affect both cooling and warming SLFCs.

In SEA, SAF and South and Central America (SAM and MCA) emissions of methane and BC are presently high while CO_2 emissions are low compared to other regions. This results in a net warming impact after 10 years that is substantially higher than that of CO_2 alone. Combined with low cooling contributions, this suggests that there is a higher potential for mitigation by targeting only SLCF emissions in these regions. As in the global case, the higher potential stems primarily from methane from the agriculture and waste management sectors, with additional potential in the energy sector especially in MCA (see "Data Availability" for sectoral data within each region). In SAF, emissions of BC from the residential and transport sectors also play an important role. In contrast, emissions from the industry sector in most regions cause a net negative impact on global temperature change. The energy sector is characterized by competing cooling and warming SLCFs, leaving CO_2 as the primary driver of net near-term warming when considering the sector as a whole, i.e., without accounting for production and combustion sub-categories as discussed above.

3.2 Temperature response to idealized policy cases and further applications

The results above suggest that strategies for emission reductions clearly can play out very differently in terms of net impact on global temperature across source region and sector. To illustrate the importance of considering co-emissions and how our dataset may be used further, we now calculate the effect on global temperature in the near- and long-term of emission changes following example polices in three global sectors (ENE, AGR and SHP). The policies are assumed to be motivated by either *i)* air quality improvements (policy 1, P1), *ii)* methane reductions (as part of the SDG agenda or climate mitigation) (P2) or *iii)* CO_2 reductions/climate targets (P3), each resulting in a different package of emission reductions (Table 2). The global temperature effect resulting from elimination of these emissions after 10 and 100 years is shown in Fig.3, for each individual policy and the combination of all three.

The energy sector can be sub-divided into fossil fuel production/distribution and combustion categories. An air quality-driven policy (P1), implementing end-of-pipe measures, would strongly reduce SO_2 and NOx emissions but would not affect the methane contribution. As shown by the top bar in Fig.3, the subsequent near-term temperature impact would be a warming due to removal of cooling aerosols, adding to the warming of methane for the sector as a whole. A significant fraction of methane emissions, originating from the production stage, could be mitigated separately from most other SLCFs, with added benefits in terms of reduced CO_2 and/or BC (P2, P3), resulting in a notable reduction in both the near- and long-term impact of the sector. Similarly, policies for the agriculture sector can be designed to target different sources addressing either primarily nitrogen losses (bringing air quality benefits but unmasking nitrate cooling) or focusing on methane sources. However, unsurprisingly only policies with strong methane reductions (here, P2) would give a significant change in the temperature impact of the sector. The net impact of the shipping sector (SHP) is a cooling in the near-term, which has been shown in several previous studies (e.g., Berntsen & Fuglestvedt, 2008; Fuglestvedt et al., 2009). Policies that reduce shipping emissions of SO_2 and NOx (P1) hence result in an added near-term warming, also when simultaneous elimination of the sector's CO_2 emissions occur (P2). A hypothetical CO_2-only policy (P3) gives a net cooling on both time scales but would fail to address the environmentally detrimental impacts of the sector pollution emissions.

This example is simplified but meant to illustrate the applicability of our dataset and how it allows for detailed analyses without further use of complex models. Furthermore, while we here calculate the temperature impact following a pulse of emissions, i.e., assuming that the policies

https://doi.org/10.5194/esd-2020-9
Preprint. Discussion started: 16 March 2020

instantaneously affect the sectoral emission composition, our pulse-based emission metrics can easily be used to study changes over time to any emission or policy scenario through convolution (Aamaas et al., 2013), allowing for a broad potential for further use of our data (see Sect. 2). In the next section, we use precisely this method to quantify the impact of temporally evolving emissions according to the most recent set of scenarios.

3.3 Contributions from SLCFs and CO_2 to global temperature change under the SSPs

While knowledge of the present-day emission composition and net temperature impact over time is essential to support mitigation design and implementation, real-world emissions will evolve following a combination of socioeconomic developments, technological advancement and policy adoption. Next, we investigate plausible pathways for the future impact of SLCFs and CO_2 by quantifying the global temperature change over the period 1900-2100 to regional and sectoral emissions following the SSPs. In the following paragraphs, we focus on four of the nine SSPs (SSP1-1.9, SSP2-4.5, SSP3-7.0 and SSP5-8.5) that span the range of future emission evolutions. See "Data Availability" for results from remaining scenarios. Figure 4 shows the evolution of temperature response under the SSPs for our source regions, with corresponding results for the global economic sectors given in Fig. S1.

Our emissions regions not only have large differences in terms of present-day emissions, but also in past evolution. This historical contribution, which was not captured in the analysis of the first half of the paper, brings NAM and EUR as the two largest contributors to the present-day warming (Fig. 4a) due to their much higher past CO_2 emissions, in line with previous literature (Höhne et al., 2011; Skeie et al., 2017). While presently being the largest emission source, EAS only surpasses EUR and NAM in net temperature impact between 2020 and 2030 when the cumulative effect of CO_2 is accounted for. In SSP1-1.9, where emissions of CO_2 decline strongly during the first half of the century in all regions, the net temperature response levels off or starts to decline in the second half of the century. We note that negative CO_2 emissions are not included in these calculations. In the remaining scenarios, the net temperature impact increases over the century for all regions. EAS remains the largest contributor, whereas in SSP5-8.5 SAS overtakes NAM as the second most important region by 2100 and SAF reaches the same order of magnitude as EUR.

Globally, the net temperature response following emissions from the ENE sector becomes larger than that due to AGR and RES in the early 2000s under this emission evolution (Fig. S1a), and ENE remains the largest individual sector until 2100 in all scenarios. The global mean temperature impact of IND switches from a net cooling to a net warming in the late 20th century as the warming due to CO_2 accumulates and overwhelms the cooling from SO_2.

While the contribution from CO_2 to the net warming becomes dominant by 2100 for most regions and sectors under all SSP scenarios, the relative importance of SLCFs and CO_2 continue to be highly variable across emission source over time, in particular under SSP3-7.0 and SSP5-8.5. This can be seen in Fig.4b, where we break down the future net temperature response in 2030, 2050 and 2100 into individual contributions from methane, CO_2, BC and the sum of SO_2

and NOx. Here we show a selection of the source regions that differ notably in composition and temporal trend. See Fig. S2 for remaining regions and Fig.S1b for breakdown by global sector.

The SSPs differ in both climate forcing targets and stringency of air pollution control, as well as underlying socioeconomic development. SSP1-1.9 is characterized by low societal challenges to mitigation and adaptation, and strong climate and air quality policies, resulting in rapidly declining emissions of both SLCFs and CO_2. However, even for strong air pollution there is a differentiation between high-, medium- and low-income countries, with a substantial time lag in the latter two (Rao et al., 2017). For example, emissions of SO_2 in SAS and SAF decline less than in other regions, subsequently maintaining a significant cooling contribution to the temperature change. In the intermediate scenario, SSP2-4.5, there is a reduction in emissions, but this is delayed and slower compared to SSP1-1.9. In SSP3-7.0, the world follows a path with more inequality and conflict, where only weak air pollution control is implemented and the end-of-century climate forcing, and hence CO_2 emissions, is higher. Subsequently, emission trends and SLCF contributions display more regional heterogeneity. There is a particularly strong projected increase in methane emission in South Asia, Africa and South America in this scenario. While EAS remains the region with the largest warming impact by 2100 in all scenarios, the contributions to warming from methane and BC in SAF and SAS surpasses those of EAS in 2100 in both SSP3-7.0 and SSP5-8.5. As CO_2 emissions increase, the net temperature response to emissions in SAS increases from close to zero to a significant warming. SSP5-8.5 is characterized by high challenges to mitigation and high climate forcing in 2100, but strong air pollution control since high use of fossil fuels would otherwise result in unbearable air pollution levels. Combined, this leads to increasing temperature impact due to increasing CO_2 emissions, but lower SLCF impacts than in SSP3-7.0, but with a non-negligible contribution from methane for several regions. Hence, in medium- and low-income regions, SLCFs, and in particular methane, are projected to play a continued important role for future temperature change. Or put another way, the potential for climate mitigation highlighted in Fig.2 is only realized in SSP1-1.9.

Clearly, and as expected, the largest difference in SLCF contributions to temperature response is between SSP1-1.9 and SSP3-7.0. To see where the largest additional climatic benefit can be gained from moving from an SSP3-7.0 world to one in line with SSP1-1.9, we show the difference in temperature between these two scenarios in 2030, 2050 and 2100 in Fig.5. Results are shown by region and sector, for all combinations where the temperature difference is greater than ±0.01°C. Our results emphasize the importance, for both near- and long-term climate change, of the strong sources of methane; agriculture, energy and waste management, especially in Africa, South Asia and South America. Fig.5. also shows how the strong SLCF mitigation in SSP1-1.9, relative to SSP3-7.0, results in a net warming contribution to climate for some region-sector combinations, such as industry in East and South Asia. As shown by the panel on the right-hand side of Fig. 5, for most sector/region combinations, around 10% of the avoided (or added) warming from strong mitigation would be realized already by 2030, and around 40-50% by 2050.

4 Discussion

In terms of avoided global warming, there is much to be gained by moving from a global emission pathway following SSP3-7.0 to one following SSP1-1.9, including contributions from reductions of SLCFs, as discussed above. Such rapid reductions of air pollutants' emissions are technically possible drawing on experience in both developed and developing countries (Crippa et al., 2016; Kanaya et al., 2019; Klimont et al., 2017) but would require simultaneous strengthening of institutions to enforce the laws. The focus of such policies would differ between OECD countries and the developing world. Further measures in the OECD would primarily focus on reducing emissions from residential heating, non-road transportation, and agriculture while assuring enforcement of legislation in power and industry. For methane, reducing venting and increasing utilization of associated petroleum gas in oil and gas exploration, increased use of biogas from waste, as well as addressing agriculture emissions should be a priority, and the technical potential for considerable reductions until 2050 exists (Höglund-Isaksson et al., 2020). A recent study suggests that anthropogenic fossil methane emissions may be significantly underestimated (Hmiel et al., 2020), and as such, reductions may be even more critical. The rapidly industrializing and developing countries would need to further strengthen legislation for the power, industry, transport sectors, introduce new laws to improve waste management, reduce emissions from agriculture, and provide wide access to clean fuels securing cooking and heating needs. Several of these policies would secure achievements of SDG goals (Rafaj et al., 2018). For methane, similar suite of measures is needed as for the developed world although waste management requires larger transformation and there is additional significant potential to reduce emissions from coal mining sector. Specific measures for improving air quality while contributing to climate change mitigation have recently been assessed for South East Asia (UNEP, 2019) and Latin America (UNEP, 2018). While previous decades have seen a southeastward shift in air pollution emissions, from high income regions at northern latitudes to East and South Asia, recent trends and the SSPs suggest that a second shift may be underway, where, as shown above, contributions from SLCFs to temperature change increase in the Middle East and Africa. An increasing carbonization in Africa south of the Sahara, primarily due to the increasing use of oil in the transport sector, has already been observed (Steckel et al., 2019), highlighting the need for further focus on this region.

SSP3-7.0 and SSP1-1.9 not only differ in the stringency of the assumed air pollution control, but also in socioeconomic development and end-of-century climate forcing. To isolate the role of air pollution policies in the transition to a low warming pathway, a companion scenario to SSP3-7.0 has been developed, the SSP3-lowNTCF (Gidden et al., 2019). Here, the socioeconomic narrative is the same, but emission factors for the short-lived species are assumed to be in line with those in SSP1-1.9. The result is similar global CO_2 emission but up to 60% reductions in global SLCF emissions in SSP3-lowNTCF relative to SSP3-7.0. Using the SSP3-lowNTCF emissions as input, we find that this in turn leads to a net temperature response to total global emissions in 2100 that is 13% lower in SSP3-LowNTCF than in SSP3-7.0 (an absolute difference of 0.5°C, from 3.7°C to 3.2°C in our calculations). For comparison the net temperature response is 71% (or 2.6°C) lower in SSP1-1.9 compared to SSP3-7.0.

https://doi.org/10.5194/esd-2020-9
Preprint. Discussion started: 16 March 2020

The potential for near-term mitigation by targeting BC emissions in the transport and residential sectors has been highlighted earlier (e.g., UNEP, 2011). We also find notable BC contributions from the residential sector in some regions, mainly South Asia and Africa, but estimate quite low BC effects from the transport sector. This has three main reasons. Firstly, since earlier studies (done about 10 years ago) there have been significant changes in legislation, and new diesel trucks and cars are (in several regions) equipped with particulate filters removing effectively BC. By now these vehicles represent a significant part of the fleet in many regions and the trend is expected to continue. Secondly, by accounting for the rapid adjustments associated with BC (Stjern et al., 2017), which reduces the net warming climate impact of the aerosols, we estimate a lower temperature response than earlier literature. Finally, we account for cooling from nitrate aerosols from emissions of NOx, for which the transport sector is a significant source, even in regions where stricter vehicle emission standards (e.g., Euro 5) have been adopted.

The AGTP is a well-established framework that has been applied in several studies of attribution of temperature impacts to emission sources (e.g., Lund et al., 2017; Sand et al., 2015; Stohl et al., 2015). It allows us to investigate the effects of individual species, sources and scenarios, which would be confounded by the low signal-to-noise ratio in fully coupled models, but also introduces caveats. Importantly, the AGTP metric is linear and does not include saturation effects as emissions and atmospheric concentrations increase. We emphasize that the absolute magnitude of temperature changes should therefore be interpreted with care, as this method is primarily designed to study relative importance and relationships between individual emissions and sources. Our analysis reflects the best estimate input data, but results have considerable uncertainty. As shown in Fig. 2a, we estimate a 1 standard deviation range in the total net temperature response on the 10-year time horizon of ±0.01°C, about 38% of the net temperature response of 0.03°C (the range is considerably lower on the 100-year time scale as the RF of SLCFs is much more uncertain than that of CO_2). This excludes uncertainties in emissions and climate sensitivity. Uncertainties in emission inventories are difficult to quantify, but generally considered lowest for CO_2 and SO_2 emissions, and high for carbonaceous aerosols (Hoesly et al., 2018). Moreover, recent studies point to emission trends that are not accurately represented in the global inventory, such as SO_2 and NOx in China (Zheng et al., 2018) and fossil fuel CH_4 emissions (Hmiel et al., 2020). However, due to high spatiotemporal variability and lack of consistent data, a comprehensive uncertainty analysis at the regional and sectoral level is challenging. The impulse response function (IRF) used in the present analysis yields an equilibrium climate sensitivity (ECS) of 0.885 K $(Wm^{-2})^{-1}$, which is in the upper range reported by Bindoff et al. (2013), but lower than many recent estimates (Forster et al., 2019). While the former has a spatiotemporal dependence, changes in the ECS mostly act to scale estimates for all sectors and regions but is less important for their ranking. Furthermore, our analysis is limited to temperature change as a measure of climate impacts. SLCFs, and in particular aerosols, also play a key role in shaping local and regional hydrology and dynamics. Comparing the SSP3-7.0 and SSP3-lowNTCF scenarios, Allen et al. (2020) recently found a significant precipitation increase due to removal of aerosols, with the strongest moistening trends over Asia. An increase in the Asian summer monsoon precipitation in scenarios with strong air pollution reductions was also recently found by Wilcox et al. (2020). Hence, further studies using coupled models are needed to fully capture the effects of the SLCFs under SSPs on local climate and environment.

5 Conclusions

Complimentary mitigation of CO_2 and other LLGHG with SLCFs is of key importance for achieving the climate ambitions of the Paris Agreement and meeting the Sustainable Development Goals. Here we show that there is significant potential for mitigation of near- and long-term temperature change, but also possible trade-offs, inherent in the present-day emissions from the major source regions and economic sectors. In terms of contributions from SLCFs, we reinforce the importance of the major emitters of methane, in particular agriculture and waste management, but also energy production, for reducing near-term warming. In contrast to the existing potential, we find that SLCFs are projected to continue to play an important role for global temperature change over the 21st century under most of the Shared Socioeconomic Pathway (SSP) scenarios. Several of the SSPs project a particularly strong increase in emissions in Africa south of the Sahara. In addition to the focus on South and East Asia as the major current sources of SLCFs, enabling technological development and legislation implementation on the African continent may be of key importance for a transition from high air pollution SSP3-7.0 pathway towards one in line with SSP1-1.9, which in turn would add reduction in global warming already over the next couple of decades. The large spatiotemporal heterogeneity in emissions trends and subsequent temperature responses underlines the need to go beyond global emission scenarios. By assessing the global temperature response to emissions from 13 regions, 7 sectors and 4 scenarios we provide a more comprehensive dataset than, to our knowledge, currently exists, enabling further analysis of mitigation strategies and economic analyses at a detailed level.

Data availability

All output data is publicly available via Figshare (https://doi.org/10.6084/m9.figshare.11386455)

Author contributions

Lund led the study, prepared the input data and wrote the paper. Aamaas performed the emission metric and uncertainty calculations. Stjern and Samset produced the graphics. Klimont and Berntsen contributed to the design of the analysis. All authors contributed to the manuscript preparation.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

The authors acknowledge funding from the Research Council Norway grant no. 248834 (QUISARC).

References

Aamaas B., Peters G. P. & Fuglestvedt J. S.: Simple emission metrics for climate impacts, Earth Syst. Dynam. 4(1), 145-170, 10.5194/esd-4-145-2013, 2013.

Aamaas B., Berntsen T. K. & Samset B. H.: The regional temperature implications of strong air quality measures, Atmos. Chem. Phys. 19(24), 15235-15245, 10.5194/acp-19-15235-2019, 2019.

Allen R. J., Turnock S., Nabat P., Neubauer D., Lohmann U., Olivie D., Oshima N., Michou M., Wu T., Zhang J., Takemura T., Schulz M., Tsigaridis K., Bauer S. E., Emmons L., Horowitz L., Naik V., van Noije T., Bergman T., Lamarque J. F., Zanis P., Tegen I., Westervelt D. M., Le Sager P., Good P., Shim S., O'Connor F., Akritidis D., Georgoulias A. K., Deushi M., Sentman L. T., Fujimori S. & Collins W. J.: Climate and air quality impacts due to mitigation of non-methane near-term climate forcers, Atmos. Chem. Phys. Discuss. 2020, 1-30, 10.5194/acp-2019-1209, 2020.

AMAP: AMAP Assessment 2015: Black carbon and ozone as Arctic climate forcers. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 2015.

Anenberg S. C., Schwartz J., Shindell D., Amann M., Faluvegi G., Klimont Z., Janssens-Maenhout G., Pozzoli L., Dingenen R. V., Vignati E., Emberson L., Muller N. Z., West J. J., Williams M., Demkine V., Hicks W. K., Kuylenstierna J., Raes F. & Ramanathan V.: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls, Environmental Health Perspectives. 120(6), 831-839, doi:10.1289/ehp.1104301, 2012.

Arneth A., Unger N., Kulmala M. & Andreae M. O.: Clean the Air, Heat the Planet?, Science. 326(5953), 672-673, 10.1126/science.1181568, 2009.

Berntsen T. & Fuglestvedt J.: Global temperature responses to current emissions from the transport sectors, Proc Natl Acad Sci U S A. 105(49), 19154-19159, 10.1073/pnas.0804844105, 2008.

Bindoff N. L., Stott P. A., AchutaRao K. M., Allen M. R., Gillett N., Gutzler D., Hansingo K., Hegerl G., Hu Y., Jain S., Mokhov I. I., Overland J., Perlwitz J., Sebbari R. & Zhang X.: Detection and Attribution of Climate Change: from Global and Regional, 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, UK and New York, NY, USA., 2013.

Bond T. C., Doherty S. J., Fahey D. W., Forster P. M., Berntsen T., DeAngelo B. J., Flanner M. G., Ghan S., Kärcher B., Koch D., Kinne S., Kondo Y., Quinn P. K., Sarofim M. C., Schultz M. G., Schulz M., Venkataraman C., Zhang H., Zhang S., Bellouin N., Guttikunda S. K., Hopke P. K., Jacobson M. Z., Kaiser J. W., Klimont Z., Lohmann U., Schwarz J. P., Shindell D., Storelvmo T., Warren S. G. & Zender C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, Journal of Geophysical Research: Atmospheres. 118(11), 5380-5552, 10.1002/jgrd.50171, 2013.

Boucher O. & Reddy M. S.: Climate trade-off between black carbon and carbon dioxide emissions, Energy Policy. 36(1), 193-200, https://doi.org/10.1016/j.enpol.2007.08.039, 2008.

Bowerman N. H. A., Frame D. J., Huntingford C., Lowe J. A., Smith S. M. & Allen M. R.: The role of short-lived climate pollutants in meeting temperature goals, Nature Climate Change. 3, 1021, 10.1038/nclimate2034, 2013.

CCAC: Air pollution in Asia and Pacific: Science-based solution, 2019.

Crippa M., Janssens-Maenhout G., Dentener F., Guizzardi D., Sindelarova K., Muntean M., Van Dingenen R. & Granier C.: Forty years of improvements in European air quality: regional policy-industry interactions with global impacts, Atmos. Chem. Phys. 16(6), 3825-3841, 10.5194/acp-16-3825-2016, 2016.

Etminan M., Myhre G., Highwood E. J. & Shine K. P.: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophysical Research Letters. 43(24), 12,614-612,623, 10.1002/2016gl071930, 2016.

Forster P. M., Maycock A. C., McKenna C. M. & Smith C. J.: Latest climate models confirm need for urgent mitigation, Nature Climate Change, 10.1038/s41558-019-0660-0, 2019.

Fuglestvedt J., Berntsen T., Eyring V., Isaksen I., Lee D. S. & Sausen R.: Shipping Emissions: From Cooling to Warming of Climate—and Reducing Impacts on Health, Environmental Science & Technology. 43(24), 9057-9062, 10.1021/es901944r, 2009.

Fuglestvedt J. S., Shine K. P., Berntsen T., Cook J., Lee D. S., Stenke A., Skeie R. B., Velders G. J. M. & Waitz I. A.: Transport impacts on atmosphere and climate: Metrics, Atmospheric Environment. 44(37), 4648-4677, https://doi.org/10.1016/j.atmosenv.2009.04.044, 2010.

Geoffroy O., Saint-Martin D., Olivié D. J. L., Voldoire A., Bellon G. & Tytéca S.: Transient Climate Response in a Two-Layer Energy-Balance Model. Part I: Analytical Solution and Parameter Calibration Using CMIP5 AOGCM Experiments, Journal of Climate. 26(6), 1841-1857, 10.1175/jcli-d-12-00195.1, 2013.

Gidden M. J., Riahi K., Smith S. J., Fujimori S., Luderer G., Kriegler E., van Vuuren D. P., van den Berg M., Feng L., Klein D., Calvin K., Doelman J. C., Frank S., Fricko O., Harmsen M., Hasegawa T., Havlik P., Hilaire J., Hoesly R., Horing J., Popp A., Stehfest E. & Takahashi K.: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci. Model Dev. 12(4), 1443-1475, 10.5194/gmd-12-1443-2019, 2019.

Haines A., Amann M., Borgford-Parnell N., Leonard S., Kuylenstierna J. & Shindell D.: Short-lived climate pollutant mitigation and the Sustainable Development Goals, Nature Climate Change. 7(12), 863-869, 10.1038/s41558-017-0012-x, 2017.

Harmsen M., Fricko O., Hilaire J., van Vuuren D. P., Drouet L., Durand-Lasserve O., Fujimori S., Keramidas K., Klimont Z., Luderer G., Aleluia Reis L., Riahi K., Sano F. & Smith S. J.: Taking some heat off the NDCs? The limited potential of additional short-lived climate forcers' mitigation, Climatic Change, 10.1007/s10584-019-02436-3, 2019.

Hienola A., Partanen A.-I., Pietikäinen J.-P., O'Donnell D., Korhonen H., Matthews H. D. & Laaksonen A.: The impact of aerosol emissions on the 1.5 °C pathways, Environmental Research Letters. 13(4), 044011, 10.1088/1748-9326/aab1b2, 2018.

Hmiel B., Petrenko V. V., Dyonisius M. N., Buizert C., Smith A. M., Place P. F., Harth C., Beaudette R., Hua Q., Yang B., Vimont I., Michel S. E., Severinghaus J. P., Etheridge D., Bromley T., Schmitt J., Faïn X., Weiss R. F. & Dlugokencky E.: Preindustrial 14CH4 indicates greater anthropogenic fossil CH4 emissions, Nature. 578(7795), 409-412, 10.1038/s41586-020-1991-8, 2020.

Hoesly R. M., Smith S. J., Feng L., Klimont Z., Janssens-Maenhout G., Pitkanen T., Seibert J. J., Vu L., Andres R. J., Bolt R. M., Bond T. C., Dawidowski L., Kholod N., Kurokawa J. I., Li M., Liu L., Lu Z., Moura M. C. P., O'Rourke P. R. & Zhang Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emission Data System (CEDS), Geosci. Model Dev. 2018(11), 369-408, https://doi.org/10.5194/gmd-11-369-2018, 2018.

Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P. & Schöpp W.: Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model, Environmental Research Communications. 2(2), 025004, 10.1088/2515-7620/ab7457, 2020.

Höhne N., Blum H., Fuglestvedt J., Skeie R. B., Kurosawa A., Hu G., Lowe J., Gohar L., Matthews B., Nioac de Salles A. C. & Ellermann C.: Contributions of individual countries' emissions to climate change and their uncertainty, Climatic Change. 106(3), 359-391, 10.1007/s10584-010-9930-6, 2011.

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. & 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, Atmos. Chem. Phys. 15(19), 11411-11432, 10.5194/acp-15-11411-2015, 2015.

Kanaya Y., Yamaji K., Miyakawa T., Taketani F., Zhu C., Choi Y., Komazaki Y., Ikeda K., Kondo Y. & Klimont Z.: Rapid reduction of black carbon emissions from China: evidence from 2009-2019 observations on Fukue Island, Japan, Atmos. Chem. Phys. Discuss. 2019, 1-28, 10.5194/acp-2019-1054, 2019.

Klimont Z., Kupiainen K., Heyes C., Purohit P., Cofala J., Rafaj P., Borken-Kleefeld J. & Schöpp W.: Global anthropogenic emissions of particulate matter including black carbon, Atmos. Chem. Phys. 17(14), 8681-8723, 10.5194/acp-17-8681-2017, 2017.

Kupiainen K. J., Aamaas B., Savolahti M., Karvosenoja N. & Paunu V. V.: Climate impact of Finnish air pollutants and greenhouse gases using multiple emission metrics, Atmos. Chem. Phys. 19(11), 7743-7757, 10.5194/acp-19-7743-2019, 2019.

Lelieveld J., Evans J. S., Fnais M., Giannadaki D. & Pozzer A.: The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature. 525, 367, 10.1038/nature15371, 2015.

Lund M. T., Berntsen T. K. & Fuglestvedt J. S.: Climate Impacts of Short-Lived Climate Forcers versus CO2 from Biodiesel: A Case of the EU on-Road Sector, Environmental Science & Technology. 48(24), 14445-14454, 10.1021/es505308g, 2014a.

Lund M. T., Berntsen T. K., Heyes C., Klimont Z. & Samset B. H.: Global and regional climate impacts of black carbon and co-emitted species from the on-road diesel sector, Atmospheric Environment. 98, 50-58, https://doi.org/10.1016/j.atmosenv.2014.08.033, 2014b.

Lund M. T., Aamaas B., Berntsen T., Bock L., Burkhardt U., Fuglestvedt J. S. & Shine K. P.: Emission metrics for quantifying regional climate impacts of aviation, Earth Syst. Dynam. 8(3), 547-563, 10.5194/esd-8-547-2017, 2017.

Lund M. T., Myhre G., Haslerud A. S., Skeie R. B., Griesfeller J., Platt S. M., Kumar R., Myhre C. L. & Schulz M.: Concentrations and radiative forcing of anthropogenic aerosols from 1750 to 2014 simulated with the Oslo CTM3 and CEDS emission inventory, Geosci. Model Dev. 11(12), 4909-4931, 10.5194/gmd-11-4909-2018, 2018.

Melamed M. L., Schmale J. & von Schneidemesser E.: Sustainable policy—key considerations for air quality and climate change, Current Opinion in Environmental Sustainability. 23, 85-91, https://doi.org/10.1016/j.cosust.2016.12.003, 2016.

Myhre G., Shindell D., Brèon F.-M., Collins W., Fuglestvedt J., Huang J., Koch D., Lamarque J.-F., Lee D., Mendoza B., Nakajima T., Robock A., Stephens G., Takemura T. & Zhang H.: Anthropogenic and natural radiative forcing. 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 [Stocker, T.F., D., Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 2013.

O'Neill B. C., Kriegler E., Riahi K., Ebi K. L., Hallegatte S., Carter T. R., Mathur R. & van Vuuren D. P.: A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Climatic Change. 122(3), 387-400, 10.1007/s10584-013-0905-2, 2014.

Persad G. G. & Caldeira K.: Divergent global-scale temperature effects from identical aerosols emitted in different regions, Nature Communications. 9(1), 3289, 10.1038/s41467-018-05838-6, 2018.

Pierrehumbert R. T.: Short-Lived Climate Pollution, Annual Review of Earth and Planetary Sciences. 42(1), 341-379, 10.1146/annurev-earth-060313-054843, 2014.

Rafaj P., Kiesewetter G., Gül T., Schöpp W., Cofala J., Klimont Z., Purohit P., Heyes C., Amann M., Borken-Kleefeld J. & Cozzi L.: Outlook for clean air in the context of sustainable development goals, Global Environmental Change. 53, 1-11, https://doi.org/10.1016/j.gloenvcha.2018.08.008, 2018.

Ramanathan V. & Carmichael G.: Global and regional climate changes due to black carbon, Nature Geoscience. 1(4), 221-227, 10.1038/ngeo156, 2008.

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

Riahi K., van Vuuren D. P., Kriegler E., Edmonds J., O'Neill B. C., Fujimori S., Bauer N., Calvin K., Dellink R., Fricko O., Lutz W., Popp A., Cuaresma J. C., Kc S., Leimbach M., Jiang L., Kram T., Rao S., Emmerling J., Ebi K., Hasegawa T., Havlik P., Humpenöder F., Da Silva L. A., Smith S., Stehfest E., Bosetti V., Eom J., Gernaat D., Masui T., Rogelj J., Strefler J., Drouet L., Krey V., Luderer G., Harmsen M., Takahashi K., Baumstark L., Doelman J. C., Kainuma M., Klimont Z., Marangoni G., Lotze-Campen H., Obersteiner M., Tabeau A. & Tavoni M.: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environmental Change. 42, 153-168, https://doi.org/10.1016/j.gloenvcha.2016.05.009, 2017.

Rogelj J., Schaeffer M., Meinshausen M., Shindell D. T., Hare W., Klimont Z., Velders G. J. M., Amann M. & Schellnhuber H. J.: Disentangling the effects of CO₂ and short-lived climate forcer mitigation, Proceedings of the National Academy of Sciences. 111(46), 16325-16330, 10.1073/pnas.1415631111, 2014.

Rogelj J., Meinshausen M., Schaeffer M., Knutti R. & Riahi K.: Impact of short-lived non-CO2mitigation on carbon budgets for stabilizing global warming, Environmental Research Letters. 10(7), 075001, 10.1088/1748-9326/10/7/075001, 2015.

Rogelj J., Shindell D., Jiang K., Fifita S., Forster P., Ginzburg V., Handa C., Kheshgi H., Kobayashi S., Kriegler E., Mundaca L., Séférian R. & Vilariño M. V.: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press., 2018.

Samset B. H. & Myhre G.: Climate response to externally mixed black carbon as a function of altitude, Journal of Geophysical Research: Atmospheres. 120(7), 2913-2927, 10.1002/2014JD022849, 2015.

Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestvedt J. S., Osprey S. & Schleussner C.-F.: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions, Geophysical Research Letters. 45(2), 1020-1029, 10.1002/2017gl076079, 2018.

Sand M., Berntsen T. K., von Salzen K., Flanner M. G., Langner J. & Victor D. G.: Response of Arctic temperature to changes in emissions of short-lived climate forcers, Nature Climate Change. 6, 286, 10.1038/nclimate2880 https://www.nature.com/articles/nclimate2880#supplementary-information, 2015.

Shindell D., Kuylenstierna J. C. I., Vignati E., van Dingenen R., Amann M., Klimont Z., Anenberg S. C., Muller N., Janssens-Maenhout G., Raes F., Schwartz J., Faluvegi G., Pozzoli L., Kupiainen K., Höglund-Isaksson L., Emberson L., Streets D., Ramanathan V., Hicks K., Oanh N. T. K., Milly G., Williams M., Demkine V. & Fowler D.: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security, Science. 335(6065), 183-189, 10.1126/science.1210026, 2012.

Shindell D. & Smith C. J.: Climate and air-quality benefits of a realistic phase-out of fossil fuels, Nature. 573(7774), 408-411, 10.1038/s41586-019-1554-z, 2019.

Shine K. P., Fuglestvedt J. S., Hailemariam K. & Stuber N.: Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases, Climatic Change. 68(3), 281-302, 10.1007/s10584-005-1146-9, 2005.

Shoemaker J. K., Schrag D. P., Molina M. J. & Ramanathan V.: What Role for Short-Lived Climate Pollutants in Mitigation Policy?, Science. 342(6164), 1323-1324, 10.1126/science.1240162, 2013.

Skeie R. B., Fuglestvedt J., Berntsen T., Peters G. P., Andrew R., Allen M. & Kallbekken S.: Perspective has a strong effect on the calculation of historical contributions to global warming, Environmental Research Letters. 12(2), 024022, 10.1088/1748-9326/aa5b0a, 2017.

Smith S. J. & Mizrahi A.: Near-term climate mitigation by short-lived forcers, Proceedings of the National Academy of Sciences. 110(35), 14202-14206, 10.1073/pnas.1308470110, 2013.

Steckel J. C., Hilaire J., Jakob M. & Edenhofer O.: Coal and carbonization in sub-Saharan Africa, Nature Climate Change, 10.1038/s41558-019-0649-8, 2019.

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. & Voulgarakis A.: Rapid Adjustments Cause Weak Surface Temperature Response to Increased Black Carbon Concentrations, Journal of Geophysical Research: Atmospheres. 122(21), 11,462-411,481, 10.1002/2017JD027326, 2017.

Stohl A., Aamaas B., Amann M., Baker L. H., Bellouin N., Berntsen T. K., Boucher O., Cherian R., Collins W., Daskalakis N., Dusinska M., Eckhardt S., Fuglestvedt J. S., Harju M., Heyes C., Hodnebrog Ø., Hao J., Im U., Kanakidou M., Klimont Z., Kupiainen K., Law K. S., Lund M. T., Maas R., MacIntosh C. R., Myhre G., Myriokefalitakis S., Olivié D., Quaas J., Quennehen B., Raut J. C., Rumbold S. T., Samset B. H., Schulz M., Seland Ø., Shine K. P., Skeie R. B., Wang S., Yttri K. E. & Zhu T.: Evaluating the climate and air quality impacts of short-lived pollutants, Atmos. Chem. Phys. 15(18), 10529-10566, 10.5194/acp-15-10529-2015, 2015.

Søvde O. A., Prather M. J., Isaksen I. S. A., Berntsen T. K., Stordal F., Zhu X., Holmes C. D. & Hsu J.: The chemical transport model Oslo CTM3, Geosci. Model Dev. 5(6), 1441-1469, 10.5194/gmd-5-1441-2012, 2012.

Takemura T. & Suzuki K.: Weak global warming mitigation by reducing black carbon emissions, Scientific Reports. 9(1), 4419, 10.1038/s41598-019-41181-6, 2019.

UNEP: Integrated Assessment of Black Carbon and Tropospheric Ozone, 2011.

UNEP: The Emissions Gap Report 2017. United Nations Environment Programme (UNEP), Nairobi, 2017.

UNEP: Integrated Assessment of Short-lived Climate Pollutants in Latin America and the Caribbean., 2018.

UNEP: Air Pollution in Asia and the Pacific: Science-based Solutions. UNEP, Paris. , 2019.

Unger N., Bond T. C., Wang J. S., Koch D. M., Menon S., Shindell D. T. & Bauer S.: Attribution of climate forcing to economic sectors, Proceedings of the National Academy of Sciences. 107(8), 3382-3387, 10.1073/pnas.0906548107, 2010.

Wilcox L. J., Liu Z., Samset B. H., Hawkins E., Lund M. T., Nordling K., Undorf S., Bollasina M., Ekman A. M. L., Krishnan S., Merikanto J. & Turner A. G.: Accelerated increases in global and Asian summer monsoon precipitation from future aerosol reductions, Atmos. Chem. Phys. Discuss. 2020, 1-30, 10.5194/acp-2019-1188, 2020.

Xu Y. & Ramanathan V.: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes, Proceedings of the National Academy of Sciences. 114(39), 10315-10323, 10.1073/pnas.1618481114, 2017.

Zheng B., Tong D., Li M., Liu F., Hong C., Geng G., Li H., Li X., Peng L., Qi J., Yan L., Zhang Y., Zhao H., Zheng Y., He K. & Zhang Q.: Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions, Atmos. Chem. Phys. 18(19), 14095-14111, 10.5194/acp-18-14095-2018, 2018.

https://doi.org/10.5194/esd-2020-9
Preprint. Discussion started: 16 March 2020

Tables:

Table 1: Constants of the Geoffroy et al. (2013) IRF.

	Mode 1	Mode 2
c_j	0.587	0.413
d_j (years)	4.1	249

Table 2: Summary of policies and species reduced.

Sector	Policy 1 (P1)	Policy 2 (P2)	Policy 3 (P3)
ENE	End-pipe measures	Reducing losses in oil and gas and flaring	Capture methane in coal mining
	SO_2, NOx	CH_4, BC, CO_2	CH_4, CO_2
AGR	Nitrogen use efficiency	Meat reduction	Increase in biogas use
	NH_3, NOx	CH_4, NH_3, NOx	NH_3, CO_2
SHP	Scrubbers and particulate filters	Slow-steaming	CO_2-only policy
	SO_2, NOx, BC	CO_2, SO_2, NO_x, BC	CO_2

https://doi.org/10.5194/esd-2020-9
Preprint. Discussion started: 16 March 2020

Figures:

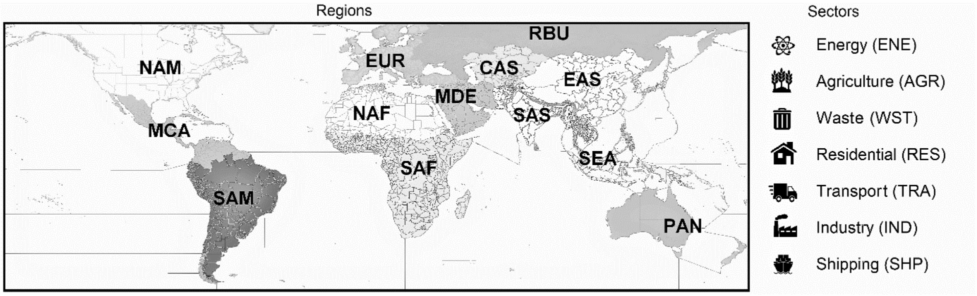

Figure 1: Emission source regions and sectors used in the analysis.

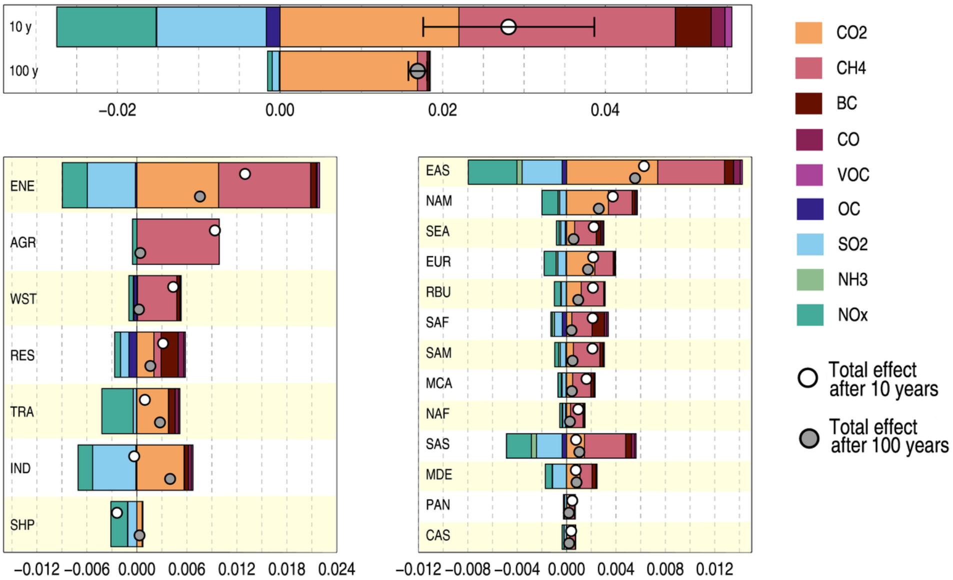

Figure 2: Global-mean surface temperature impact 10 and 100 years after one year of present-day (i.e., year 2014) emissions of SLCFs and CO$_2$ for: a) global total emissions, b) emissions from seven major economic sectors, and c) total (i.e., sum of all sectors) emissions in 13 sources regions. Panels b and c are sorted by total net effect on the 10-year timescale (white circle). Error bars (±1 standard deviation) in the top panel represent the range in total net temperature impact due to uncertainties in radiative forcing.

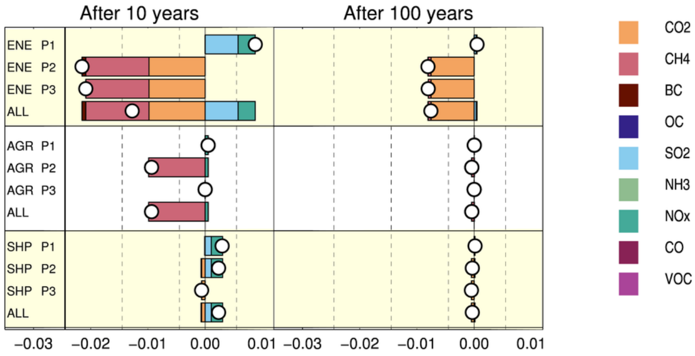

Figure 3: Global-mean surface temperature impact after 10 and 100 years resulting from instantaneous reductions of different sets of SLCFs and CO₂ emissions under three different policies, as well as for these three combined. White circles indicate the net impact.

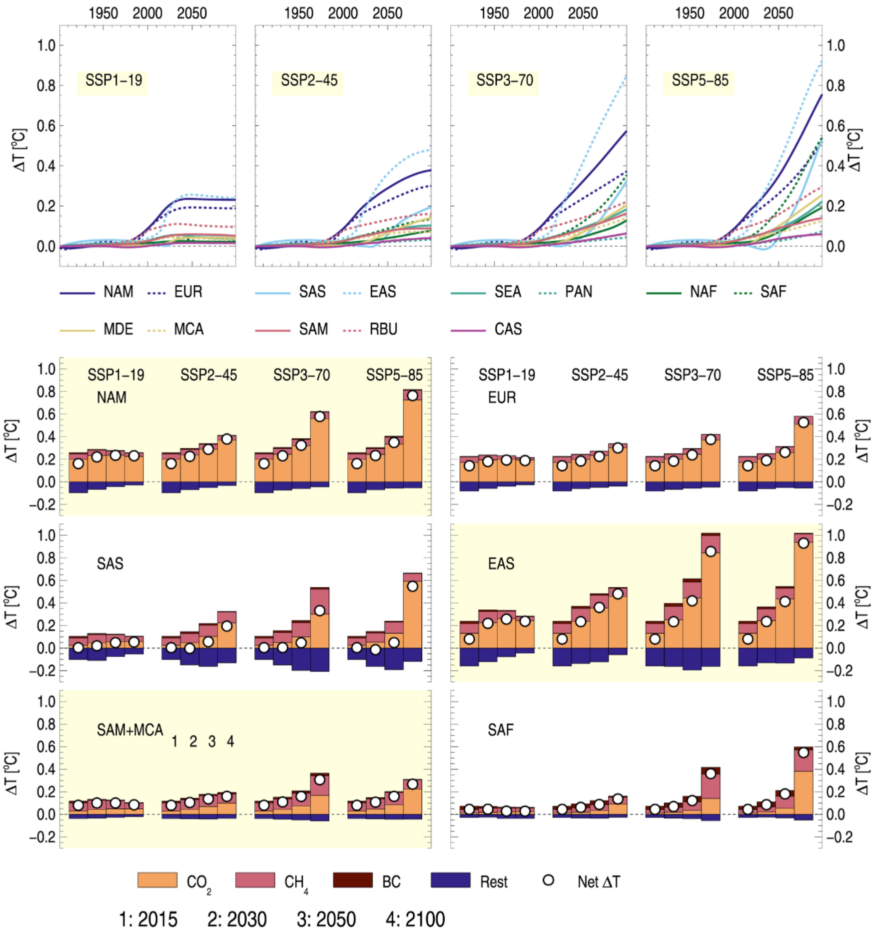

Figure 4: Global mean temperature response to historical emissions and future SSP pathways: a) Net (i.e., sum over all species and sectors) response over the period 1900 to 2100 for each region and scenario and b) net response in 2015, 2030, 2050 and 2100 to emissions in six regions broken down by contributions from CO_2, BC, methane and the sum of SO_2, OC, NH_3 and ozone precursors (i.e., "Rest").

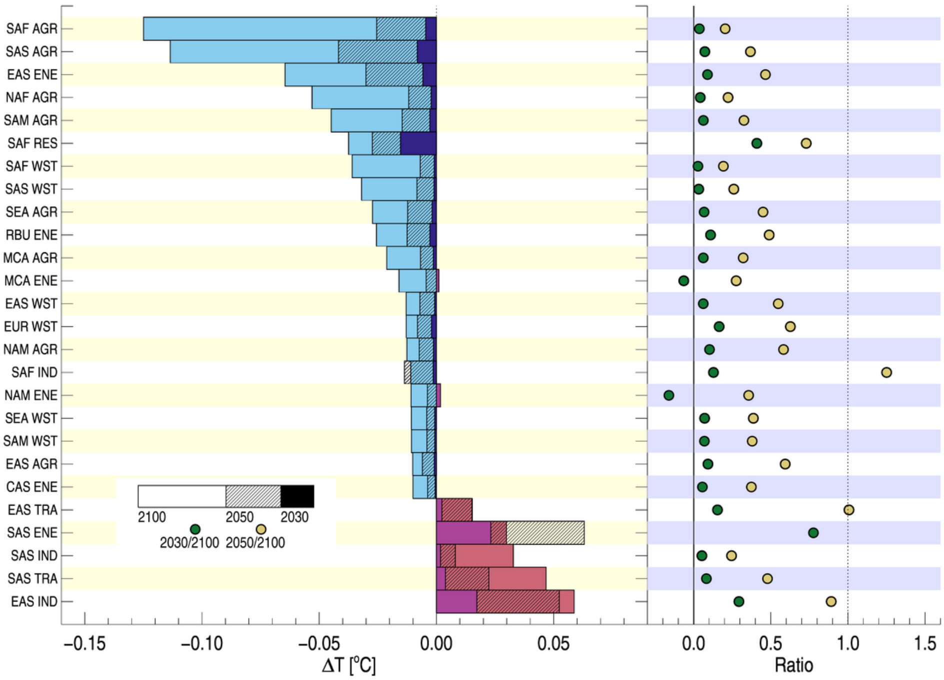

Figure 5: Difference in net SLCF (i.e., sum of all components except CO_2) temperature response between SSP1-1.9 and SSP3-7.0 in 2030, 2050 and 2100 by region and sector. Only combinations of sectors and regions where the differences in global temperature response is larger than ±0.01 °C are shown. For each of these combinations, the panel on the right shows the ratio between the temperature response difference in 2030 and 2100 and between 2050 and 2100.