We thank for the constructive and helpful comments from the Reviewers. Our answers are given in red. When we have accepted the suggestion, this is given by an “OK”.

Reviewer 1:

General Comments

This is a well written and interesting study that explores how optimal mitigation of short-lived climate forcers could contribute to cooling (or reduced warming) over the next few decades. It provides useful information for policymakers considering how to limit warming through non-CO2 measures. There are, of course, many uncertainties, but this study demonstrates very nicely what could be done. My main concern is that the uncertainties in the ARTP values should be discussed more deeply than they are currently; this also extends to better explanations of the error bars on some of the figures (see below). If this point and the other, relatively minor points below are addressed, then I am happy to recommend publication in ACP.

We have added more details on the ARTP values, such as what processes are included, how they were estimated in the studies we refer to, as well as on uncertainties. We have also edited the explanations of the error bars. See specific replies below.

Specific Comments

In the Abstract, clarify that mitigation of some SLCFs (e.g. SO2) leads to warming. We have added this sentence to the abstract: “On the other hand, mitigation of other SLCFS (e.g., SO2) leads to warming.”

P1 l7 Change text to: ‘…policies is, however, still uncertain.’ OK

P1 l21 ‘outsized impact’ -> large impacts? OK

P2 l7 SLCFs -> SLCF OK

P2 l19 I think you need to say something like “…may lower the global temperature by 0.22C in 2041-2050 compared to a reference scenario.” OK

P2 l19 “complete removal of anthropogenic aerosol emissions (BC, OC, SO2)…” SO2 is, of course, an aerosol precursor, not an aerosol. “Complete” seems excessive, as I don’t think you mean removal of species like NOx and NH3 (which are also aerosol precursors), so I would use slightly less all-encompassing language here. We have revised the sentence to:
“In comparison, a complete removal of anthropogenic emissions of black carbon (BC), organic carbon (OC) and SO2 (sulphate aerosol precursor) would induce a global mean surface heating of 0.5–1.1°C, according to four recent climate models (Samset et al., 2018).”

P2 l22 “…a range of the UN SDGs.” This is a bit vague – presumably you mean air quality, food security, etc. Can you be a little more specific? We have reworded and extended this part to:
“Going beyond temperature and precipitation impacts, SLCF emission mitigation is also known to have multiple co-benefits and trade-offs with the UN Sustainable Development Goals (Haines et al., 2017). The co-benefits are generally larger than the trade-offs. Among the most well-known co-benefits, we find that SLCF mitigation will reduce air pollution and, hence, reduce premature deaths (SDG3), as well as reduce crop losses (SDG2).”

P2 l24 potential of SLCFs. OK

P2 l29 delete 'that' OK

P2 l32 State year for 'current legislation' – 2019? The year for current is 2015 in the emission dataset, so we added "(2015)" in the sentence.

P3 l1 technically OK

P3 l20, l22 capitalise Absolute OK

P3 l25 How well constrained/model dependent are the (crucial) ARTP values? This is rather important and deserves some discussion. For example, is nitrate aerosol included in the model(s)? How are the indirect effects of aerosols handled in the model(s)? Do the models include interactive vegetation, e.g., that responds to air pollution induced damage? How do the models represent the mixing state of aerosols? Do we have any idea about how these missing processes (I am assuming they are missing) will affect the model results? I appreciate that you can only use state-of-the-art models to make your best estimate of temperature responses, but some discussion of how uncertain the results (ie ARTP values) are should be included, to give some perspective. I note you do quote errors on your values – but I think these cover just the known unknowns. We have added a couple of paragraphs in the method section (Section 2.3) on the ARTP values and what processes they include.

"The ARTP dataset utilized here are presented in detail by Aamaas et al. (2017), including how they were estimated, the processes included, and the robustness. That paper built on RF values calculated by Bellouin et al. (2016). The paper applied four different coupled chemistry-climate models or CTMs. They compared control simulations with perturbed simulations where emissions were reduced by 20% for one species and one emission region. We apply the average values across models. For the aerosols and aerosol precursors, three out of four models included the aerosol direct and first indirect (cloud-albedo) effect. RF for BC deposition on snow and ice surfaces and the semi-direct effect was estimated in one of the models. For the ozone precursors (NOx, CO, and VOC) and CH_4, RF is modelled for the aerosol direct effect and first indirect effects, short-lived ozone effect, methane effect, and methane-induced ozone effect. Nitrate aerosols are also considered based on results from one model.

The matrix of regional response coefficients (RCS), which enables us to go from regional RFs to regional temperature responses and ARTPs, are also presented in detail by Aamaas et al. (2017). The RCS values are mostly based on coefficients modelled by Shindell and Faluvegi (2009). A weakness with our chosen method is that Shindell and Faluvegi (2009) is to our knowledge the only study that provide the necessary relationships between regional RFs and regional temperatures to create RCS values."

We have also some more text in the paragraph about uncertainties in Section 2.3:

"Previous work by Aamaas et al. (2016) shows that the assumption of independent radiative forcing uncertainties gives a total uncertainty range for emission reductions for a mix of species that is similar to the range seen between different models. Further, they also found robustness for the method we use here to estimate temperature changes, such as models agreeing on whether different mitigation scenarios lead to warming or cooling."

P5 l18-l26 Please quote values +/- errors correctly. It is incorrect to quote -0.33 +/- 0.083 C. The error should probably only be quoted to one significant figure, although you may feel justified to quote to two, as you have done. But the value then needs to be quoted to the same number of decimal places as the error, i.e. it should be, e.g., -0.335 +/- 0.083 C, or -0.33 +/- 0.08 C. The same inconsistency appears on several of the subsequent lines. We have edited how we quote the errors, mostly to one significant figure.

P6 l2 on -> in OK

P6 l5 on -> to OK

P7 l2 estimates OK

P7 l11 usage -> use OK

P7 l20 it contributes -> they contribute OK

P8 l14 values -> value OK

P8 l15 is -> are OK

P8 l24 SLCFs reduction -> SLCF reductions OK

P8 l30 implicitly OK

P9 l3 how -> what OK

P9 l18 …may be smaller than those estimated here… OK

Figure 2 caption should explain the origin of the error bars. We have added:
"Error bars representing 1 standard deviation are given for the net response in 2030, 2050, and 2100. They are calculated based on literature values for gaussian uncertainties in per-component RF, assuming no inter-species correlation, and estimated using a Monte Carlo analysis (100 000 pulls) where component forcing values are drawn from within the uncertainty distributions."

Figure 4 caption should explain the origin of the error bars (on the global values). We have added:
"Error bars representing 1 standard deviation are given for the sectors for the global temperature response. They are calculated based on literature values for gaussian uncertainties in per-component RF, assuming no inter-species correlation, and estimated using a Monte Carlo analysis (100 000 pulls) where component forcing values are drawn from within the uncertainty distributions."

Figure 5 caption – the explanation of the error bars could be clearer. We have edited to:
"Error bars representing 1 standard deviation are included. The blue and black error bars are calculated based on literature values for gaussian uncertainties in per-component RF, assuming no inter-species correlation, and estimated using a Monte Carlo analysis (100 000 pulls) where component forcing values are drawn from within the uncertainty distributions. The blue error bars indicate the uncertainty for the emission regions, the black error bars for the emission sectors. The grey error bars are estimated from uncertainty in the climate sensitivity based on Monte Carlo analysis (100 000 pulls) with values drawn from within the lognormal uncertainty distribution."

Reviewer 2:

In this study, the authors investigate the potential temperature implications of stringent air quality policies, by applying matrices of regional temperature responses to new pathways for future anthropogenic emissions of aerosols, methane (CH4) and other short-lived gases. This is an interesting and relevant topic since there are still a lot of uncertainties on how regional temperatures are affected by ambitious SLCF emission mitigation policies.

General comments

The Introduction is too short, I suggest the authors to add more information about SLCF description. For example, here you show results for BC, OC, SO2, NOx, CO, VOC, and CH4. Some description about their cooling/warming impact of them will help to a better understand of the results. Also, maybe a bit more description of the ECLIPSE project would be good, since this works is strongly connected to it.
We have added several sentences on the ECLIPSE projects, its findings, and connections with our manuscript in the fourth paragraph of the introduction:

"That paper synthesized the work in the project ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants). The project designed realistic and effective mitigation scenarios for SLCFs and quantifying its climate and air quality impacts. The work started with producing new emission inventories for the recent past and until 2050. Those emissions were applied in several advanced Earth system models (ESMs) and chemistry transport models (CTMs). The climate impacts were estimated with two different paths of research, where the first was to calculate radiative forcing (RF) and then produce emission metrics such as ARTP. The second path was on modelling transient climate responses with ESMs. Results from the first path were applied in an integrated assessment model to identify emission mitigation measures that are both beneficial for air quality and short-term climate impact. That study found that estimates on global temperature change are similar for the decade 2041-2050 by applying these two different paths. Further, the two different research paths partly agree on how much emission changes in CH4 is responsible for the temperature change versus emission changes of the other SLCFs. Our study utilizes several aspects of the ECLIPSE research, including emission inventories, mitigation pathways, and ARTP values."

We have also added these sentences to the first paragraph of the introduction, to describe the different SLCFs in more detail:

"The SLCFs considered here are black carbon (BC), organic carbon (OC), sulphur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH4). CH4, which is a greenhouse gas and a precursor of O3 and stratospheric water vapor, is the SLCF that gives the largest warming at current emission levels. BC (also known as soot) is a result of incomplete combustion, that causes warming through absorption of sunlight and reduced albedo of contaminated snow and ice surfaces, but also cooling, mainly from affecting clouds. Removing all anthropogenic BC emissions would cause a cooling of -0.05 °C according to Stohl et al. (2015). Several aerosols are cooling the climate through scattering solar radiation and altering the radiative properties of clouds, with sulphate aerosol formed from SO2 and ammonia (NH3) giving the largest cooling. Stohl et al. (2015) estimate that removing all anthropogenic emissions of SO2 would increase the global temperature by 0.69 °C. OC is another cooling aerosol, of which a complete removal of anthropogenic OC emissions would lead to a warming of 0.13 °C (Stohl et al., 2015). The ozone-precursors NOx, CO, and VOC produce tropospheric O3, which is a greenhouse gas. Emissions of these species will also impact the hydroxyl radical (OH) concentration, which impacts CH4. The impact of current emissions of these ozone precursors is small compared to the impact of current emissions of CH4 and SO2."

Some figures are not well described in the text, for example, the authors directly mention Fig. 2 or 3 after describing a result obtained. The figures should be defined saying what it is representing there, and if needed, some explanation about how to interpret the graphic (if I got it right, the different symbols in fig 3 shows the influence of the different sectors of that region in a latitude band). This

way it will be easier to follow the text. Please, do it whenever the figure has not been described in advanced. There is also a lack of mention some figures that I will point out in the technical comments.
We have clearer presented the figures in the text. Further, we have added several callouts to the figures in the text. We have added a sentence for captions for Figure 3 and 4 that explains the symbols.

A better organization of the results must be done. It would be better to organize them in subsections, like "Global/Regional temperature change" or/and "Results by regions", as an example. Furthermore, more quantitative results could be added. Complementing with a table would be helpful for a better overview of the results found in this study (and comparing the results found in Stohl et al., 2015). We have added subtitles. These are Global temperature change, Regional temperature change, Temperature change by emission region, Temperature change by emission sector, Uncertainties. We have also added a table (Table 2), which is an overview of the results given in Figures 2, 3, and 4. Further, we have extended the result section to clearer organize the results and present the results in more details.

Specific comments

Page 1, line 16, authors state that "cutting CH4 and BC emissions contribute the most. This could offset warming equal to approximately 15 years of current global CO2 emissions." How do you get to this conclusion? I haven't seen it in the manuscript.
This point is discussed in the third paragraph of the discussion section. We have revised the sentence to make the point clearer:

"The net global cooling could offset warming equal to approximately 15 years of current global CO2 emissions."

Page 2, line 24, when mentioning the work of Stohl et al., 2015, although the authors mention it throughout the text, it will be good to have more description of the what they found. See reply to the first general comment by the Reviewer. We have expanded this paragraph to better present ECLIPSE, including some of their findings.

Page 2, line 29, here the description of the scenarios is done. I have several comments:

- The description of the SLCP_scen is not clear for me, so the difference is that the SLCP_scen only has 50 different mitigation measures on SLCFs compared to the 2 MTFR; a) how many has the MTRF scenario? And b) in what is it based to be called optimal? We have added one sentence regarding a): "The model behind includes more than 2000 technologies to control air pollutant emissions and 500 options to control greenhouse gas emissions." b) SLCP_scen is optimal in the sense of reducing the global temperature, hence, climate-optimal. This should be clearer with the new table (see point below) and modified description.

- It would be helpful to have the scenarios description as a list or as a table with a short description. We have produced a table (Table 1) as an overview of the three different scenarios. Some sentences from the text have been moved into the table.

- Check that you call the baseline scenario as "baseline" in the text. There are couple of times where you call it CLP, and sometimes is confusing to follow all the acronyms. We think the Reviewer is pointing out to CLE. We have either replaced CLE with baseline or added the word baseline in the text.

Page 3, line 7, IIASA has not been described. We have written out “The International Institute for Applied Systems Analysis”.

Page 5, line 5, do you refer to the results shown in figure 5? If so, you could refer to it here. We refer to Figure 5 in the last section of the results section. We prefer not to link a figure from the results section to the method section.

Page 5, line 20, “The global temperature change is calculated as the area-weighted sum of the net regional changes given by equation 1.” Can be added to the subsection 2.2, after describing the ARTP. We have moved this sentence to Section 2.3, as this section is most suitable for this information.

Page 5, line 28, “a warming of more tan 0.2ºC” how do you get this value? This finding is from Figure 2a, which we now have added a call-out to in the previous sentence. We have also revised the sentence to better reflect that this warming is solely from the reduction of the cooling components, by adding “from those”.

Page 6, what about the warming temperature response found in fig. 3b and 4b? Authors only focus on cooling temperature response results. This comment could point to two different issues. First, that we don’t discuss the warming responses. But we describe the net effects, which is a combination of the warming and cooling temperature responses. Second, and most likely point raised, that we don’t present the findings in Figures 3b and 4b. We do write about these results and have added callouts to the b-figures to show this clearer.

Page 7, line 14, to what scenario does the value -0.33 ºC correspond? We have added “in SLCP_scen” in the sentence.

Technical comments

Page 1, line 13, “using existing regional temperature change potential (ARTP)” did you mean, using absolute existing regional temperature change potential? OK

Page 1, line 25, add a comma after “pollution”. OK

Page 3, line 16, move “in Table 3 in Stohl et al. (2015) ” to the beginning of the sentence in line 15 to avoid “Stohl et al. (2015). Stohl et al. (2015) ” OK

Page 4, line 14, “CLE” to “baseline”. OK

Page 5, line 25, add Fig. 2A somewhere in this line. OK

Page 5, line 30, add Fig. 2B somewhere in this line. OK

Page 6, line 9, “CLE” to “baseline”. We have changed to “baseline CLE”.

Page 6, line 14, in “mitigation scenarios” do the authors refer to MTRF?. If so:
Page 6, line 14, add Fig. 3b after “rest of the World”. This sentence refers to both Figure 3A and 3B. We have added references to both Figure 3a and 3b in the paragraph.

Page 6, line 21, it should be Fig. 4a. OK

Page 6, line 25, add Fig. 3b after “to cooling.”. OK

Page 10, line 11, doi is missing. But the DOI is there already: 10.1146/annurev-environ-052912-173303

The regional temperature implications of strong air quality measures

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Abstract. Anthropogenic emissions of short-lived climate forcers (SLCFs) affect both air quality and climate. How much regional temperatures are affected by ambitious SLCF emission mitigation policies~~,~~ is ,however, still uncertain. We investigate the potential temperature implications of stringent air quality policies, by applying matrices of regional temperature responses to new pathways for future anthropogenic emissions of aerosols, methane (CH_4) and other short-lived gases. These measures have only minor impact on CO_2 emissions. Two main options are explored, one with climate optimal reductions (i.e. constructed to yield a maximum global cooling) and one with maximum technically feasible reductions. The temperature response is calculated for four latitude response bands (90-28° S, 28° S-28° N, 28-60° N, and 60-90° N) by using existing Absolute ~~r~~Regional T~~t~~emperature change P~~p~~otential (ARTP) values for four emission regions: Europe, East Asia, shipping, and the rest of the world. By 2050, we find that global surface temperature can be reduced by -0.3±0.08 °C with climate-optimal mitigation of SLCFs relative to a baseline scenario, and as much as -0.7 °C in the Arctic. Cutting CH_4 and BC emissions contribute the most. The net global cooling~~is~~ could offset warming equal to approximately 15 years of current global CO_2 emissions. On the other hand, mitigation of other SLCFS (e.g., SO_2) leads to warming. If SLCFs are mitigated heavily, we find a net warming of about 0.1 °C, but when uncertainties are included a slight cooling is also possible. In the climate optimal scenario, the largest contributions to cooling comes from the energy, domestic, waste, and transportation sectors. In the maximum technically feasible mitigation scenario, emission changes from the sectors industry, energy, and shipping will give warming. Some measures, such as in the sectors agriculture waste burning, domestic, transport, and industry, have ~~outsized~~ large impacts on the Arctic, especially by cutting BC emissions in winter in areas near the Arctic.

1 Introduction

Poor air quality is an issue of global concern, with health and welfare impacts affecting billions of people (WHO, 2016;Dockery et al., 1993;Di et al., 2017). Additionally, many of the components that make up air pollution, also lead to radiative forcing impacting climate, through scattering or absorbing solar radiation, or by acting as greenhouse gases (Myhre et al., 2013b;von Schneidemesser et al., 2015). The net and individual climate impacts of present emissions of such short-lived climate forcers (SLCFs) have been extensively studied, but are however still poorly constrained (Stohl et al., 2015;Aamaas et al., 2016;Myhre et al., 2017;Samset et al., 2018). The SLCFs considered here are black carbon (BC), organic carbon (OC), sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). CH_4, which is a greenhouse gas and a precursor of O_3 and stratospheric water vapor, is the SLCF that gives the largest warming at current emission levels. BC (also known as soot) is a result of incomplete combustion, that causes warming through absorption of sunlight and reduced albedo of contaminated snow and ice surfaces, but also cooling, mainly from affecting clouds. Removing all anthropogenic BC emissions would cause a cooling of -0.05 °C according to Stohl et al. (2015). Several aerosols are cooling the climate through scattering solar radiation and altering the radiative properties of clouds, with sulphate aerosol formed from SO_2 and ammonia (NH_3) giving the largest cooling. Stohl et al. (2015) estimate that removing all anthropogenic emissions of SO_2 would increase the global temperature by 0.69 °C. OC is another cooling aerosol, of which a complete removal of anthropogenic OC emissions would lead to a warming of 0.13 °C (Stohl et al., 2015). The ozone-precursors NO_x, CO, and VOC produce tropospheric O_3, which is a greenhouse gas. Emissions of these species will also impact the hydroxyl radical (OH) concentration, which impacts CH_4. The impact of current emissions of these ozone precursors is small compared to the impact of current emissions of CH_4 and SO_2.

In the coming decades, mitigation of CO_2 and other long-lived greenhouse gases (LLGHGs) is vital for the success of the goals in the Paris Agreement (UNEP, 2016). Concurrently, we expect large changes in SLCF emissions, in response to air quality policies, additional climate change mitigation efforts, and due to co-emissions with LLGHGs. As some SLCFs cool the climate, others warm it, and some may do both at different times after emission, the exact mitigation pathways of SLCFs will be of importance for the near-term rate and magnitude of warming – both globally and regionally. While several studies have analysed the impact on CO_2 mitigation of SLCFs (e.g., Rogelj et al., 2014), our study does not consider CO_2 emissions, but investigates a set of air quality measures that mainly influence SLCF~~s~~ emissions.

Designing mitigation measures with both air quality and climate change in mind is however not straightforward, as warming SLCFs are often co-emitted with cooling SLCFs. Some authors have argued that a mitigation focus on SLCFs can be counterproductive, as this may lead to relaxing efforts on reducing CO_2 emissions (Pierrehumbert, 2014;Shoemaker et al., 2013). However, if this is done in a consistent way using emission metrics with appropriate time-horizons, this can be avoided (Berntsen et al., 2010). Another argument against SLCF mitigation today is that the long-term cooling potential of emission reductions is limited, and that delaying mitigation of SLCFs has only minor impact on temperature stabilization and peaking in the future (e.g., Pierrehumbert, 2014). However, SLCF mitigation is already occurring as part of air quality policy (Li et al., 2017) and is expected to continue in the coming decades regardless of the level of climate mitigation ambitions (Victor et al., 2015;Rao et al., 2017). Stohl et al. (2015) showed (applying the Absolute Regional Temperature change Potential (ARTP) methodology) that climate optimal reductions of SLCFs, i.e. the combination of measures which maximize temperature reduction, may lower the global temperature by 0.22 °C in 2041-2050 compared to a reference scenario. In comparison, a complete removal of anthropogenic emissions of black carbon (BC), organic carbon (OC) and SO_2 (sulphate aerosol precursor)~~aerosol emissions (BC, OC and SO_2)~~ would induce a global mean surface heating of 0.5–1.1°C, according to four recent climate models (Samset et al., 2018). Going beyond temperature and precipitation impacts, SLCF emission mitigation is also known to have multiple co-benefits and trade-offs~~close links~~ with ~~a range of~~ the UN Sustainable Development Goals (SDGs) (Haines et al., 2017). The co-benefits are generally larger than the trade-offs. Among the most well-known co-benefits, we find that SLCF mitigation will reduce air pollution and, hence, reduce premature deaths (SDG3), as well as reduce crop losses (SDG2).

Recently, Stohl et al. (2015) gave a general overview of the temperature reduction potential of SLCFs. That paper synthesized the work in the project ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants). The project designed realistic and effective mitigation scenarios for SLCFs and quantifying its climate and air quality impacts. The work started with producing new emission inventories for the recent past and until 2050. Those emissions were applied in several advanced Earth system models (ESMs) and chemistry transport models (CTMs). The climate impacts were estimated with two different paths of research, where the first was to calculate radiative forcing (RF) and then produce emission metrics such as ARTP. The second path was on modelling transient climate responses with ESMs. Results from the first path were applied in an integrated assessment model to identify emission mitigation measures that are both beneficial for air quality and short-term climate impact. That study found that estimates on global temperature change are similar for the decade 2041-2050 by applying these two different paths. Further, the two different research paths partly agree on how much emission changes in CH4 is responsible for the temperature change versus emission changes of the other SLCFs. Our study utilizes several aspects of the ECLIPSE research, including emission inventories, mitigation pathways, and ARTP values. We~~Our study~~ explore~~s~~ the~~se~~ findings in Stohl et al. (2015) further for individual emission regions and emission sectors using updated data and methods, following pathways that focus on air quality concerns. Our focus is on the temperature effects of SLCFs, however, mitigation of these components can also help to achieve several of the Sustainable Development Goals (Shindell et al., 2017).

A detailed look into what sectors and regions ~~that~~ contribute to the mitigation potential from SLCF reductions requires a comprehensive emission dataset. As part of the ECLIPSE project, emission inventories and scenarios for future emissions (for the period 1990-2050) of SLCFs were produced (Klimont et al., 2017;Klimont et al., In prep.). The scenarios describe three different futures with different mitigating ambitions (see Table 1), one baseline with current legislation (CLE), one with as much mitigation of SLCFs as possible (MTFR), and one which only include measures that lead to net global cooling~~.~~ ~~The baseline scenario assumes implementation of current legislation (CLE). Both current and planned environmental laws are included while considering known delays, but assuming full enforcement in the future~~ (Stohl et al., 2015). ~~The most ambitious mitigation scenario is labelled “the maximum technical feasible reductions” (MTFR), where SLCFs are cut as much as possible (although without changes in consumer behaviour, structural changes in transport, agriculture or energy supply or additional climate policies) due to air quality concerns. This is a very policy demanding scenario~~ The MTFR is demanding, as emissions of SLCFs are cut~~, as most emissions are reduced~~ by 60-80 % within a few decades. However, similar trends have historically been seen for emissions of SO_2 and NO_x in Western Europe and North America (Amann et al., 2013;Rafaj et al., 2015). The third scenario can be seen as a subset of MTFR, as this climate-optimal mitigation scenario ($SLCP_{\_scen}$) includes roughly 50 different mitigation measures on SLCFs from the MTFR catalogue of measures that avoid warming. The scenario name $SLCP_{\_scen}$, based on the scenario name SLCP given by The International Institute for Applied Systems Analysis (IIASA), should not be mixed up with the term short-lived climate pollutant. ~~Only measures that are estimated to lead to net global cooling, while reduction of co-emitted cooling species are accounted for, are included.~~ Every selected measure gives a net cooling based on the Global Temperature change Potential values for a time horizon of 20 years, given a linear ramp-up of emission measures over a time period of 15 years (Stohl et al., 2015). These mitigation measures can be grouped into three categories of measures. First, measures on emissions of CH_4 that can be centrally implemented (e.g., recovery and use of gas from oil and gas industry). Second, technical measures on BC emissions from small stationary and mobile sources (e.g., eliminating high-emitting vehicles). Third, non-technical measures to eliminate emissions of BC (e.g., banning of open-field burning of agricultural residues). In Table 3 in Stohl et al. (2015), ~~T~~the 17 largest mitigation measures that contribute to more than 80 % of the climate benefit are ~~given in Table 3 in Stohl et al. (2015)~~. Stohl et al. (2015) showed that these measures have only minor impact on emissions of CO_2.

The global and regional temperature impact of these emission scenarios should ideally be calculated with the most advanced ~~Earth System models~~ESMs, but can be approximated and explored quickly for different emission components and sectors with emission metrics. Perturbation in the global temperature is most commonly calculated with the A~~a~~bsolute Global Temperature change Potential (AGTP) (Shine et al., 2005;Shine et al., 2007), while the regional temperature distribution in broad latitude bands can be investigated with ~~absolute~~ Absolute Regional Temperature change Potential (ARTP) (Shindell and Faluvegi, 2010). AGTP and ARTP quantify the warming per unit emission and can be seen as building blocks to analyse different emission scenarios. As described by Aamaas et al. (2017), the temporal regional temperature response of any emission scenario or difference between scenarios can be calculated with a convolution given the emission dataset and ARTP values.

In this study, we use mitigation datasets of SLCFs and regional temperature metrics to calculate the potential of SLCF mitigation for reducing global and regional temperatures. Our analysis builds on Stohl et al. (2015), while the novelty of our work is that we estimate the temperature change potentials of mitigating different emission regions and emission sectors. We investigate what species can contribute the most to spatially and temporally resolved mitigation. The methods are described in Sect. 2. The results are presented in Sect. 3 and discussed in Sect. 4. We conclude in Sect. 5.

2 Methods

2.1 The ECLIPSE dataset

The analysis in this paper is based on emission pathways from the ECLIPSE emission project (Klimont et al., 2017;Klimont et al., In prep.). Briefly, ECLIPSE estimated possible future emission values based on different ambition levels for mitigation of SLCFs. The emission pathways we use are shown in Fig. 1. Emissions are given for seven SLCFs: Black carbon (BC), organic carbon (OC), sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). The sectors included are agriculture (agr), agriculture waste burning (awb), domestic (dom), energy (ene), industry (ind), solvent (slv), transportation (tra), waste (wst), and shipping (shp). The datasets contain information on the seasonal cycle, such as larger emissions from residential heating and cooking in winter (not shown).

2.2 SLCF mitigation pathways

As we are interested in how much mitigation of SLCFs can contribute towards reducing global and regional temperatures in the next decades, we construct two mitigation datasets from these pathways. The first is the emission difference between the mitigation scenario $SLCP_{\_scen}$ (see Fig. 1~~B~~b) relative to the baseline CLE (see Fig. 1~~A~~a). The second is the emission difference between the mitigation scenario MTFR (Fig. 1~~C~~c) relative to the baseline~~CLE~~. As the MTFR dataset in the ECLIPSE project is only given for the 2030-2050 period, we assume a linear trend between 2015 and 2030 for MTFR. We use the most recent version of the datasets, ECLIPSE V5a (Klimont and Heyes, 2016). The ECLIPSE dataset is very detailed. Here, we aggregate regionally and seasonally as necessary to match the format of the ARTP values available (Aamaas et al., 2017). We interpolate linearly between the emissions points, which are given every five years and in some cases every ten or 20 years. Since the emission scenarios from ECLIPSE go until 2050, we keep emission levels constant between 2050 and 2100, as we are not aware of any scenarios that are compatible with the ECLIPSE scenarios and contain the level of detail needed for our analysis. A large share of the emissions are also mitigated by 2050; hence, the temperature potential of further emission cuts after 2050 is limited.

2.3 Regional temperature potentials (ARTP)

The ARTP values applied come from the study by Aamaas et al. (2017). They give values for each species for emissions occurring in Europe (EUR), East Asia (EAS), global shipping (SHP), and the rest of the World (ROW), as well as separating between Northern Hemisphere summer and winter emissions. The temperature response is given for four latitude response bands (90-28° S, 28° S-28° N, 28-60° N, and 60-90° N). The temperature response in latitude band l in year t is given by a convolution:

$$\Delta T_{i,r,s,l}(t) = \sum_{u=1}^{2} \int_0^t \Delta E_{i,r,s,u}(t') \times ARTP_{i,r,s,u,l}(t-t')dt' \qquad (1)$$

for species i emitted in region r from emission sector s during season u (the year is divided into two seasons, summer u=1 and winter u=2). The emission difference between a mitigation scenario and the reference scenario is ΔE. As the final year in the ECLIPSE emission scenarios is 2050, our main case is the temperature impact in 2050. The global temperature change is calculated as the area-weighted sum of the net regional changes given by equation 1.

The ARTP dataset utilized here are presented in detail by Aamaas et al. (2017), including how they were estimated, the processes included, and the robustness. That paper built on RF values calculated by Bellouin et al. (2016). The paper applied four different coupled chemistry-climate models or CTMs. They compared control simulations with perturbed simulations where emissions were reduced by 20% for one species and one emission region. We apply the average values across models. For the aerosols and aerosol precursors, three out of four models included the aerosol direct and first indirect (cloud-albedo) effect. RF for BC deposition on snow and ice surfaces and the semi-direct effect was estimated in one of the models. For the ozone precursors (NOx, CO, and VOC) and CH_4, RF is modelled for the aerosol direct effect and first indirect effects, short-lived ozone effect, methane effect, and methane-induced ozone effect. Nitrate aerosols are also considered based on results from one model.

The matrix of regional response coefficients (RCS), which enables us to go from regional RFs to regional temperature responses and ARTPs, are also presented in detail by Aamaas et al. (2017). The RCS values are mostly based on coefficients modelled by Shindell and Faluvegi (2009). A weakness with our chosen method is that Shindell and Faluvegi (2009) is to our knowledge the only study that provide the necessary relationships between regional RFs and regional temperatures to create RCS values.

Uncertainties (1 standard deviation) in the global temperature response have been estimated given a Monte Carlo analysis of 100 000 simulations. This analysis is based on a probability density function defined by model based estimates of uncertainties in direct radiative forcing from the literature (Myhre et al., 2013b;Myhre et al., 2013a) with the same treatment of radiative forcing uncertainty as in Lund et al. (2017) (see also the Supplement). Radiative forcing from each species is treated as a random variable. The distribution for the total uncertainty is derived by summing the probability density functions of all species. We assume that the radiative forcing uncertainties are independent in these calculations. Previous work by Aamaas et al. (2016) shows that the assumption of independent radiative forcing uncertainties gives a total uncertainty range for emission reductions for a mix of species that is similar to the range seen between different models. Further, they also found robustness for the method we use here to estimate temperature changes, such as models agreeing on whether different mitigation scenarios lead to warming or cooling. Also, note that the multi-model studies used as input were run with unified emissions. This particularly affects BC, where the current substantial uncertainty in annual emissions (Bond et al., 2013;Cohen and Wang, 2014) will not be represented. We compare our derived uncertainties to the influence of low and high climate sensitivities in the literature, 1.5 and 4.5 °C for a doubling of CO_2 (Bindoff et al., 2013). Here, we adopt a lognormal distribution and assume the value range covers 1 standard deviation. Uncertainties are not given for the latitude bands as a formal quantification of uncertainties for the ARTPs has not been produced.

3 Results

As our analysis can be viewed from multiple dimensions, we present the results by focusing on one and one dimension. An overview of our temperature response estimates relative to the baseline is given in Table 2, which are presented in detail in the following sections. Temperature effects in 2050 are presented for the global and regional level, for species, for emission regions, and for emission sectors.

3.1 Global temperature change

Figure 2 shows the temporal temperature response from 2010 until 2100 with the two scenarios relative to the baseline for the different species and the net response. As for the following figures, results for SLCP $_{scen}$ relative to the baseline are found in the upper panel and MTFR relative to the baseline in the lower panel. If SLCFs are mitigated in a climate-optimal manner, we estimate a maximum change in global temperature of -0.3~~3~~±0.~~083~~1 °C by 2050, relative to current legislation, increasing to about -0.4 °C later in the century ending at -0.44±0.1~~1~~ °C in 2100. (see Fig. 2a~~A~~, black line, and Table 2). ~~The global temperature change is calculated as the area-weighted sum of the net regional changes given by equation 1.~~ The temperature response of aggressive mitigation of SLCFs (MTFR) leads gradually to a small change in temperature ~~net warming~~ of 0.~~059~~1±0.~~15~~ 1 °C in 2050 relative to the baseline, which seems to be counter-productive in terms of goals limiting the global temperature increase (see Fig. 2~~B~~b). As the uncertainty interval is large, since large emission cuts of warming and cooling components cancel each other almost out (about 0.7 °C cooling and warming in 2050, see Fig. S3 in the Supplement for cooling and warming separated for both MTFR and SLCP$_{\_scen}$), we cannot rule out that this scenario may lead to cooling. In the climate-optimal scenario (SLCP$_{\_scen}$), CH_4 (-0.21±0.02~~1~~ °C in 2050 and increasing in magnitude) and BC (-0.2~~19~~±0.07~~3~~ °C in 2050) are the main drivers of the temperature reductions (Fig. 2a). The measures will also reduce co-emissions of cooling species causing a warming from those of more than 0.2 °C in 2050. The main warming contributions are emission reductions of OC and NO_x, with small impacts from other SLCFs. The main difference to the maximum reduction scenario (MTFR) is the large warming contribution for MTFR (0.4~~35~~±0.1~~2~~ °C in 2050) from SO_2 reductions, as well as additional warming from NO_x reductions (Fig. 2b).

3.2 Regional temperature change

The temperature responses in the four latitudinal bands are given in Fig. 3 for different emission regions and emission sectors, all responses are relative to the baseline. The global responses are found to the right, while the responses in the latitude bands from south to north are given from left towards right. The symbols are the net response for each emission region. In this section, we discuss differences in the response between the latitude bands. The Arctic (60-90° N) is the region that is the most sensitive to the mitigation scenarios for all emission regions (see Fig. 3 and Table 2), followed by northern mid-latitudes (28-60° N), as the climate sensitivities are largest for those regions and most of the emissions occur ~~o~~in the Northern Hemisphere (Aamaas et al., 2017). In SLCP$_{\_scen}$, the cooling in the Arctic (-0.7~~69~~ °C in 2050) is more than twice the global average. This sensitivity in the Arctic is larger than for reductions of CO_2, which would be roughly 50% when applying the ARTP concept to~~on~~ CO_2. This amplification in the Arctic is larger than the average for mitigation of European emissions and smaller for mitigation of East Asian emissions (see Fig. 3a). Measures on BC emissions during winter in the Northern Hemisphere contribute to this amplification. In terms of sectors, mitigation measures on SLCFs from agriculture waste burning, domestic, transportation, and industry have larger than average influence on the Arctic relative to the global average (Fig. 4). Some variability is also seen for the Arctic. While MTFR will lead to warming globally relative to baseline CLE, a cooling of the same magnitude is estimated for the Arctic (see Fig. 3b). The net cooling in the Arctic is driven by emissions from rest of the World, while mitigation in the shipping sector leads to warming for both and the net effect of European mitigation is near zero~~ (see Fig. 3b)~~.

3.3 Temperature change by emission region

The emission region that contributes the most in the mitigation scenarios is Rest of the World (see Fig. 3 and Table 2). In the Supplement, we indicate that rest of Asia and other developing regions are the most important regions (as seen in Stohl et al., 2015), although our ARTP dataset limits us from making clear conclusions of what sub regions have the largest cooling potential. In SLCP$_{\_scen}$, mitigation leads to cooling from all emission regions and emission sectors except global shipping (Fig. 3a). In MTFR, warming globally is estimated for rest of the world and shipping, while near zero change for Europe and a cooling contribution for East Asia (Fig. 3b).

3.4 Temperature change by emission sector

In Fig. 4, the temperature responses in the four latitudinal bands are given for different emission sectors and separated by the emitted species, all responses are relative to the baseline. The emission sectors that give the largest cooling in SLCP$_{\_scen}$ are energy, domestic, waste, and transportation (see Fig. 4~~b~~a and Table 2). In the Arctic, the order changes with domestic becoming the most important sector and transportation moved up to third place, mainly due to the large warming of BC in the Arctic. Shipping is the only sector that causes a small warming when mitigated. While MTFR lead to a net warming, only three out of the nine sectors contribute to that, the sectors industry, energy, and shipping (Fig. 4b). Even for the energy sector, mitigation in East Asia leads to cooling (Fig. 3b). Most of the mitigation measures found unsuitable in a climate-optimal scenario can be placed in those sectors.

3.5 Uncertainties

In Fig. 5, the uncertainties for the global temperature responses in Figs. 3 and 4 based on uncertainties in radiative forcing are compared to the uncertainty given different climate sensitivities. The uncertainties for the radiative forcing give generally a larger span than the climate sensitivity when a broad mix of emissions are mitigated, such as in the MTFR. For individual components, the range in climate sensitivities leads to a larger span than uncertainty in radiative forcing.

4 Discussion

The method applied here (Sect. 2.3) estimates the long-term response to a sustained change in SLCF emissions. However, in the current climate (here 2015), the climate has not reached the full response of sustained SLCF emissions at the current level due to the thermal inertia of the system. We have also estimated the temperature perturbations after 2015 running a transient simulation through 2015 using also historic emissions of SLCFs and applying the same methodology as in Sect. 2.3. The potential for temperature reductions is reduced by up to 0.04 °C in 2050 and 0.05 °C in 2100 when this masked warming is included. Hence, the actual global temperature reduction is -0.3~~0~~ °C by 2050 in SLCP$_{\_scen}$, when climate variability is excluded.

For the mean of the 2041-2050 period, our estimate of global temperature change of -0.29 °C relative to the baseline is higher than -0.22 °C calculated by Stohl et al. (2015), which may be due to the us~~ag~~e of different versions of the ECLIPSE emission datasets, as well as some updates in the ARTP values.

A temperature change in 2050 of -0.3~~3~~ °C in SLCP$_{scen}$ relative to the baseline could potentially offset a large increase in CO_2 emissions. If we weight with ARTP with a time horizon of 30 years, approximately the number of years until 2050, this temperature change is the same as about 520 Gt CO_2, or 15 years of current global CO_2 emissions. A climate optimal mitigation of SLCFs can therefore contribute to limiting the global temperature increase; however, only in addition to sustained CO_2 mitigation (e.g., Shoemaker et al., 2013).

SLCFs are mitigated due to different concerns, including that they~~it~~ contribute~~s~~ to achieving several of the Sustainable Development Goals (Shindell et al., 2017). Hence, while a climate-optimal mitigation strategy on SLCFs may be needed, in addition to reducing CO_2 emissions, to contribute in avoiding global warming above the temperature targets in the Paris Agreement, measures undertaken to reduce air pollution and other problems are likely to lead to higher levels of warming. In this respect, climate-optimized mitigation of SLCFs can be considered as a type of geoengineering, as we keep emitting cooling substances. This is not an obvious nor trivial choice due to the higher levels of air pollution it entails, and would likely meet political resistance, as the ability to also address air pollution is seen as a main motivation for SLCF mitigation (Victor et al., 2015), although the two problems are viewed as interlinked (Tvinnereim et al., 2017). Thus, the feasibility of only executing the climate-optimal measures is lower than if there were no other concerns. SLCFs mitigation will lead to numerous other benefits, reducing health problems, increasing yields from agriculture, and achieving several of the sustainable development targets (UN, 2015;Haines et al., 2017). Many of the measures with the largest overall economic benefits involve SO_2 reductions, measures that may be difficult by policymakers to neglect while prioritizing less beneficial measures that are climate-optimal. Another issue is the choice of baseline for evaluation of temperature change. We apply here the most recent ECLIPSE emission dataset from July 2015, while measures taken and planned legislation after that date will, in particular, lower SO_2 emissions. The two main consequences are that the warming impact of MTFR is probably smaller or non-existent, and that limiting the global temperature increase to 1.5 °C is harder as more SO_2 emissions are removed than in a climate-optimal SLCF mitigation scenario.

SLCFs are also co-emitted with CO_2. The ECLIPSE mitigation dataset makes use of external projections of energy use and industrial production and does not include mitigation measures directly on CO_2. Stohl et al. (2015) argue that the measures included in this study have no significant impact on CO_2 emissions. However, Rogelj et al. (2014) showed that mitigation of CO_2 will lead to reductions of SLCFs. Hence, the potential cooling effect of dedicated reductions in emissions of warming SLCFs may be limited by successful mitigation of CO_2. As global temperature may peak or stabilize some time after 2050, the temperature reduction by mitigating SLCFs can be seen as more critical at reducing this peak or level than reducing global temperature in 2050, the year we focus on in this study.

While the calculations here could also be based on AGTP values, Aamaas et al. (2017) argue that the regionality and seasonality included in the emission dataset and in the metric value give added value~~s~~. Regional responses, such as the higher efficacy in the Arctic due to emissions close to the Arctic are~~is~~ better captured than global averages. Users of these results may also find estimated temperature responses in latitude bands more interesting than a global average. While previous studies have used ARTP values to calculate the temperature impact of SLCF mitigation globally (Stohl et al., 2015) and in the Arctic (Sand et al., 2016), we also show the temperature impact in the regions where most people live, such as in the 28-60° N latitude band. For this band, the net temperature reduction in 2050 in the $SLCP_{\_scen}$ scenario relative to the baseline is 0.5~~48~~ °C, or almost 50% larger than the global average.

Emission metrics are based on the current atmospheric composition and linearity, hence, an 80 % reduction of a pollutant is assumed to give twice the impact of a 40 % reduction. While this holds for small perturbations, this assumption may be inaccurate for the large SLCF~~s~~ reductions by 2050 in the $SLCP_{\_scen}$ and MTFR scenarios. Chen et al. (2018) recently quantified the uncertainties by assuming linearity and found an error up to 15% for the direct radiative forcing efficiency for BC and OC, when assuming a total phaseout of emissions. The uncertainties can be larger for the indirect radiative forcing, especially in high emitting regions. Another assumption is the choice of constant emissions after 2050. This was chosen, as we were unable to combine with other scenarios with emission data after 2050, while a reduction of emissions to varying degree in all three scenarios may occur after 2050. Newer studies (e.g., Stjern et al., 2017;Baker et al., 2015) have also shown that the warming of BC emissions is smaller than implicitly included with the emission metric values used here; hence, the cooling potential of reducing BC emissions is likely smaller than estimated by us. However, our dataset is in the lower end of the range given by Samset et al. (2018) (0.5–1.1°C for removing all anthropogenic emissions of BC, OC, and SO_2) and thus not outside of the likely range given by state-of-the-art knowledge.

Different stakeholders may be interested in different aspects of our calculations. Decision makers can easily combine their own emission datasets with ARTP values to investigate what is most relevant for them. As the dimensions are many, we present additional figures in the Supplement, such as what~~how~~ the regional temperature change is for different times throughout the 21st century.

5 Conclusion

This study has not analysed scenarios with CO_2 mitigation or measures on SLCFs that will also result in emission cuts of CO_2. However, we have estimated the temperature effects of different air quality measures on SLCFs emissions. We have shown that mitigation of SLCFs can contribute to reduce the global and regional temperatures in the next few decades, if mitigation is optimized with regards to temperature change. On the other hand, mitigation of SLCFs to gain other benefits can be counter-productive for limiting the temperature increase, especially if we cut emissions of SO_2. A global temperature reduction from SLCF mitigation of about -0.4±0.1 °C is technically feasible in the second part of the 21st century. Emission reductions of CH_4 and BC will contribute the most. The sectors with the largest shares contributing to cooling are energy, domestic, waste, and transportation in the $SLCP_{\_scen}$ scenario, while aggressive emission cuts will lead to warming from industry, energy, and shipping. The net response in the $SLCP_{\_scen}$ scenario is almost 50% larger than the global average for the 28-60° N latitude band and more than the double for the Arctic. BC emissions drives this as BC emissions during winter in the Northern Hemisphere will have much larger contribution than when looking at global and annual averages. The Arctic is the most influenced by mitigation in the sectors domestic, energy, and transportation. The feasible temperature reductions may be smaller than those estimated here due to several reasons, such as the entangling of SLCFs and CO_2 emissions, the unlikely option by policymakers of leaving out measures that are highly beneficial for health that are not climate-optimal, and newer studies indicating a smaller temperature impact of BC emissions.

Data availability. The analysis is based on two datasets. The ECLIPSE emission data can be downloaded from http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html. The ARTP values applied can be found in Aamaas et al. (2017).

Author contribution. TKB and BA developed the idea of the study. BA compiled the needed data and modelled the regional temperature responses. BA lead the writing of the paper, with contributions from TKB and BHS.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1: An overview of the three emission scenarios with different mitigating ambitions investigated in this study. The emission inventories and scenarios for the period 1990-2050 have been produced by Klimont et al. (2017);Klimont et al. (In prep.);Stohl et al. (2015).

Scenario	Acronym	Description and mitigation measures
Baseline – current legislation	CLE	The baseline scenario assumes implementation of current (2015) legislation. Both current and planned environmental laws are included while considering known delays, but assuming full enforcement in the future.
Mitigation - maximum technically feasible reductions	MTFR	The most ambitious mitigation scenario, where SLCFs are cut as much as possible (although without changes in consumer behaviour, structural changes in transport, agriculture or energy supply or additional climate policies) due to air quality concerns. This is a very policy demanding scenario, as most emissions are reduced by 60-80 % within a few decades. The model behind includes more than 2000 technologies to control air pollutant emissions and 500 options to control greenhouse gas emissions.
Mitigation - climate-optimal mitigation scenario	$SLCP_{scen}$	A subset of MTFR containing about 50 different mitigation measures on SLCFs. Only measures that are estimated to lead to net global cooling, while reduction of co-emitted cooling species are accounted for, are included, hence, climate-optimal. These measures are technical measures on emissions of CH4 and BC, as well as non-technical measures to eliminate BC.

Table 2: The global and regional temperature responses in 2050 for $SLCP_{scen}$ and MTFR scenarios relative to the baseline CLE. Global temperature responses are given for the net, as well as for all the species, emission regions, and emission sectors at a global level. In the lower part, temperature responses in the four latitude bands are shown for global emissions. This table is a synthesis of Fig. 2, 3, and 4. The sectors included are agriculture (agr), agriculture waste burning (awb), domestic (dom), energy (ene), industry (ind), solvent (slv), transportation (tra), waste (wst), and shipping (shp).

ΔT [°C] in 2050	SLCP$_{scen}$ - CLE	MTFR - CLE
Sum	-0.3	0.1
Species	SLCP$_{scen}$ - CLE	MTFR - CLE
BC	-0.2	-0.2
OC	0.1	0.1
SO2	0.002	0.4
NOx	0.02	0.04
CO	-0.03	-0.03
VOC	-0.02	-0.02
CH4	-0.2	-0.2
Regions	SLCP$_{scen}$ - CLE	MTFR - CLE
EUR	-0.01	0.003
EAS	-0.06	-0.03
ROW	-0.3	0.05
SHP	0.002	0.03
Sectors	SLCP$_{scen}$ - CLE	MTFR - CLE
dom	-0.06	-0.05
ene	-0.1	0.05
ind	-0.02	0.1
tra	-0.04	-0.03
wst	-0.06	-0.06
awb	-0.004	-0.004
shp	0.002	0.03
agr	-0.01	-0.01
slv	-0.006	-0.005
ΔT in latitude bands	SLCP$_{scen}$ - CLE	MTFR - CLE
90° S-28° S	-0.2	-0.02
28° S-28° N	-0.3	0.1
28° N-60° N	-0.5	0.1
60° N-90° N	-0.7	-0.02

Figure 1: **The global emission levels relative to the 1990 level for baseline CLE (~~A~~a), SLCP$_{\text{\_scen}}$ (~~B~~b) and MTFR (~~C~~c). The 1990 emission level for each SLCF is normalized to 100.**

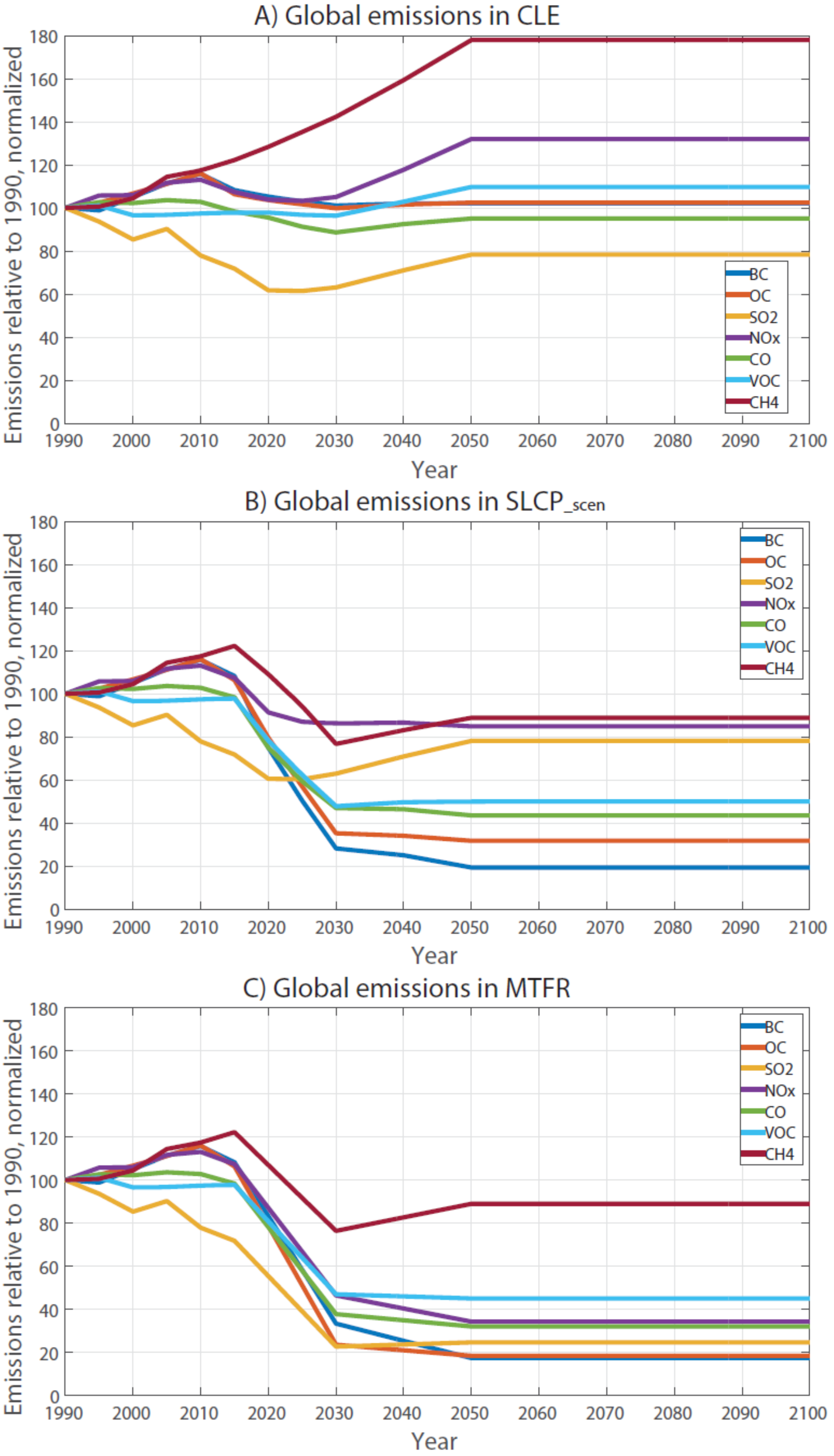
Figure 2: **Global temperature response due to the SLCP$_{\text{\_scen}}$ (a~~A~~) and MTFR (b~~B~~) scenarios ~~-~~relative to the baseline CLE scenario. Future global temperature change will also be impacted by historic and baseline emissions, which are not accounted for here. Error bars representing 1 standard deviation are given for the net response in 2030, 2050, and 2100. They are calculated based on literature values for gaussian uncertainties in per-component RF, assuming no inter-species correlation, and estimated using a Monte Carlo analysis (100 000 pulls) where component forcing values are drawn from within the uncertainty distributions.**

Figure 3: **The temperature response in the latitude bands and globally in 2050 for emission regions and emission sectors for SLCP$_{\text{\_scen}}$ (~~A~~a) and MTFR (b~~B~~) scenarios relative to the baseline CLE. The emission regions are Europe (EUR), East Asia (EAS), global shipping (SHP), and the rest of the World (ROW). The net response in the latitude bands due to emissions from each emission region is given by the symbols. The emission sectors are agriculture (agr), agriculture waste burning (awb), domestic (dom), energy (ene), industry (ind), solvent (slv), transportation (tra), waste (wst), and shipping (shp).**

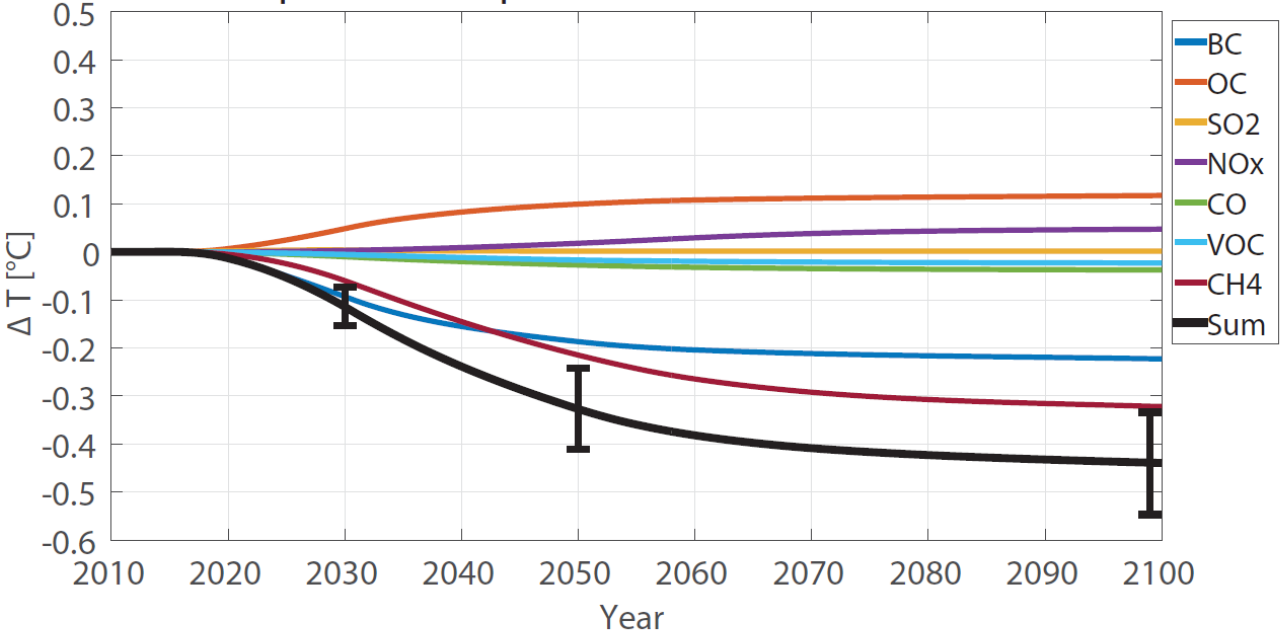
Figure 4: **The temperature response in the latitude bands and globally in 2050 for emission sectors and species for SLCP$_{\text{\_scen}}$ (~~A~~a) and MTFR scenario (~~B~~b) relative to the baseline CLE. Future global temperature change will also be impacted by historic and baseline emissions, which is not accounted for here. The emission sectors are agriculture (agr), agriculture waste burning (awb), domestic (dom), energy (ene), industry (ind), solvent (slv), transportation (tra), waste (wst), and shipping (shp). The net response in the latitude bands due to emissions from each emission sector is given by the symbols.**

Error bars representing 1 standard deviation are given for the sectors for the global temperature response. They are calculated based on literature values for gaussian uncertainties in per-component RF, assuming no inter-species correlation, and estimated using a Monte Carlo analysis (100 000 pulls) where component forcing values are drawn from within the uncertainty distributions.

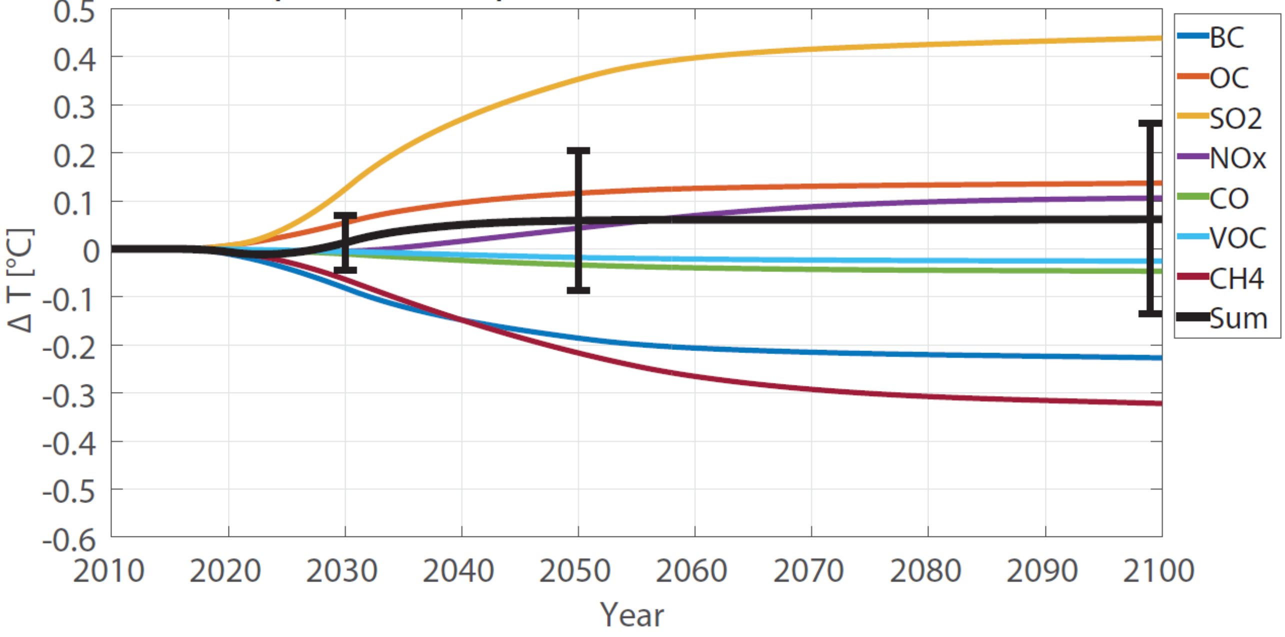
Figure 5: **The global temperature response in 2050 in mitigation scenarios relative to the baseline for emission regions and emission sectors for SLCP$_{\text{\_scen}}$ and MTFR scenario. Error bars representing 1 standard deviation are included. The blue and black error bars are calculated based on literature values for gaussian uncertainties in per-component RF, assuming no inter-species correlation, and estimated using a Monte Carlo analysis (100 000 pulls) where component forcing values are drawn from within the uncertainty distributions. The blue error bars indicate the uncertainty for the emission regions, the black error bars for the emission sectors. The grey error bars are estimated from uncertainty in the climate sensitivity based on Monte Carlo analysis (100 000 pulls) with values drawn from within the lognormal uncertainty distribution.~~1 standard deviation uncertainties are included. The blue (black) error bars indicate the 1 standard deviation in the RFs based on no inter-species correlation in the uncertainties for emission regions (emission sectors). The grey error bars show the uncertainty in the climate sensitivity.~~**


A) Global emissions in CLE
Emissions relative to 1990, normalized
Year
0
20
40
60
80
100
120
140
160
180
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
BC
OC
SO2
NOx
CO
VOC
CH4
B) Global emissions in SLCP_scen
Emissions relative to 1990, normalized
Year
BC
OC
SO2
NOx
CO
VOC
CH4
C) Global emissions in MTFR
Emissions relative to 1990, normalized
Year
BC
OC
SO2
NOx
CO
VOC
CH4

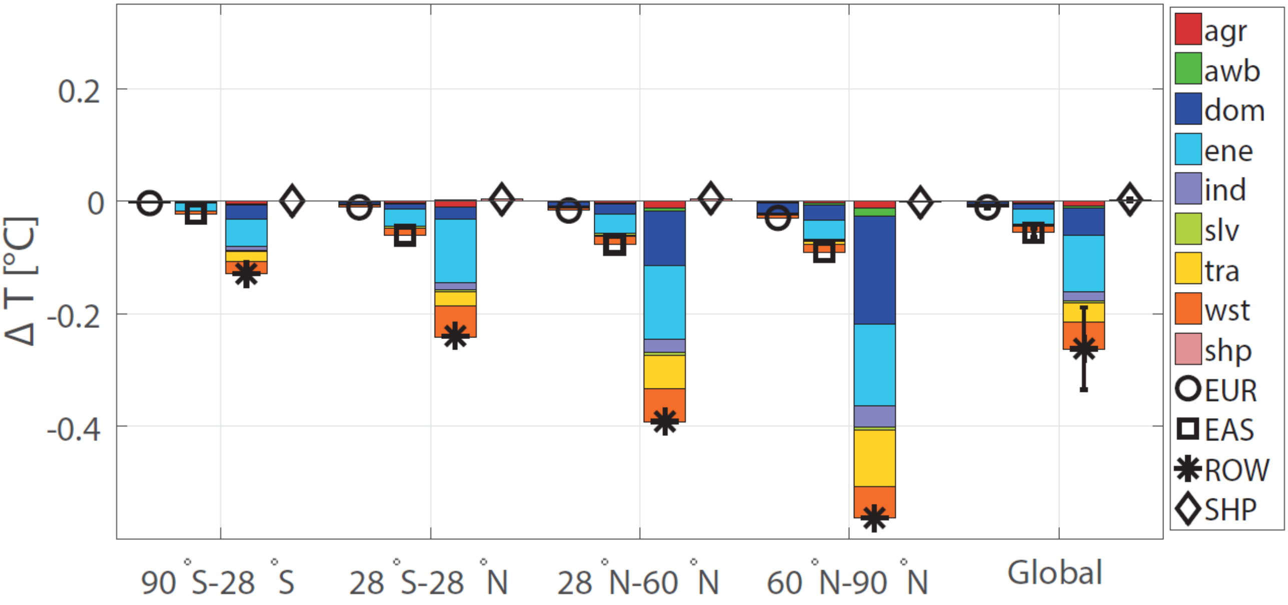
A) Global temperature response difference for SLCP$_{\_scen}$ - CLE



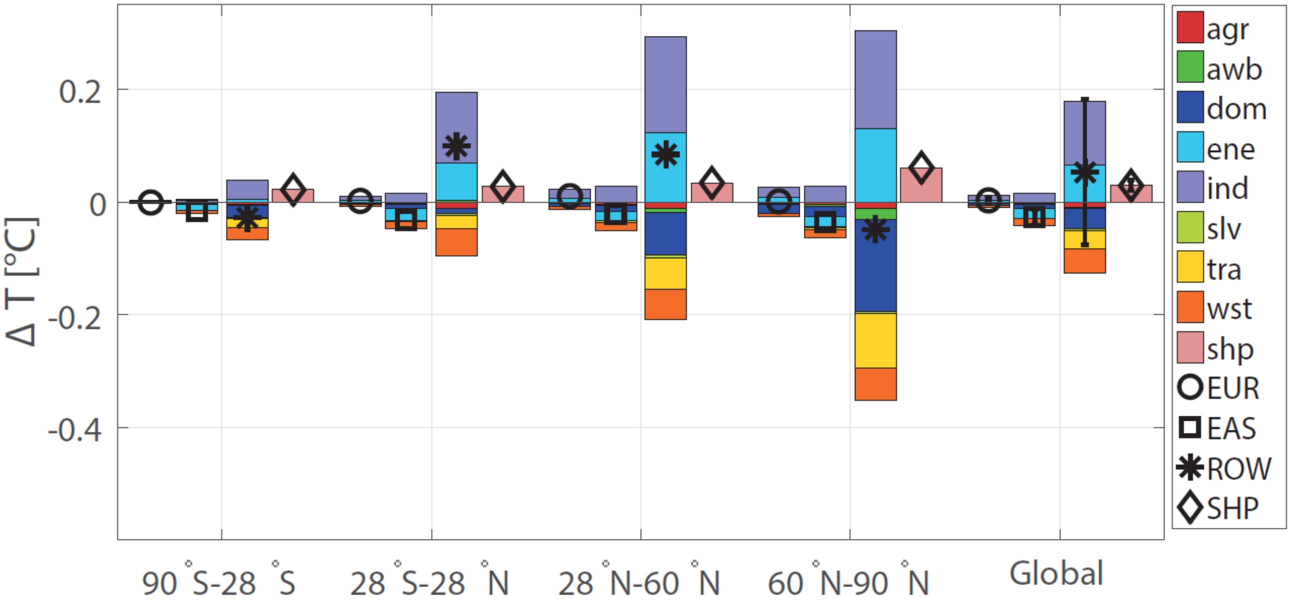
B) Global temperature response difference for MTFR - CLE

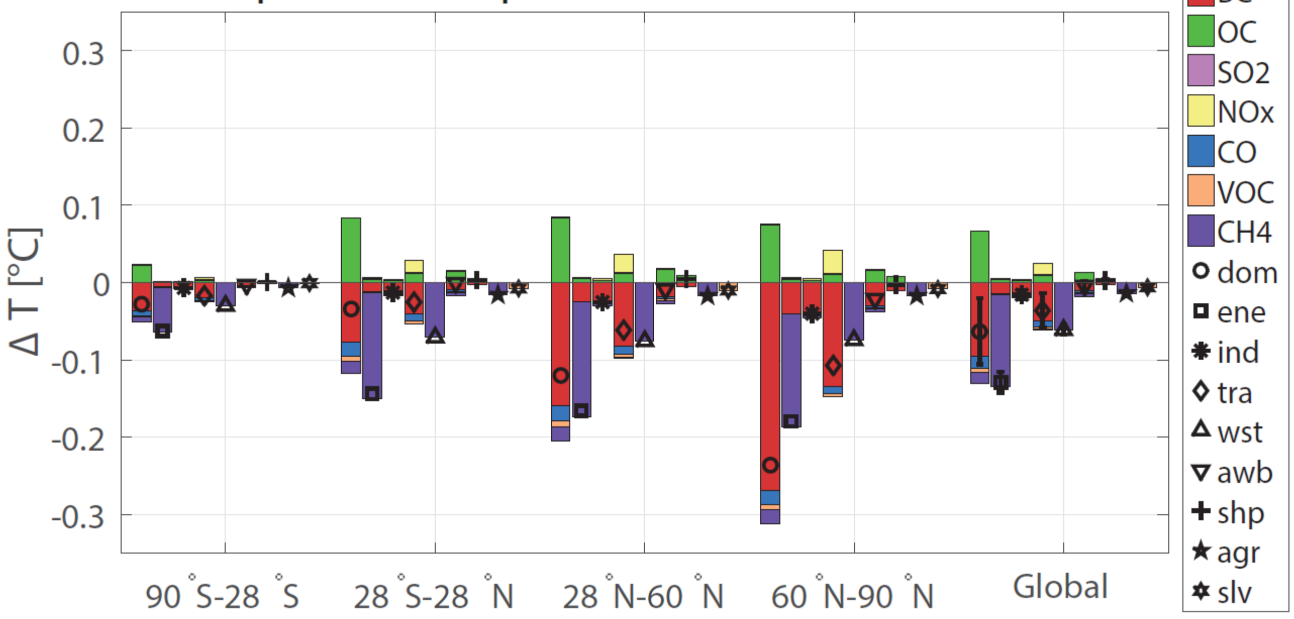


A) Temperature response in 2050, $SLCP_{\_scen}$ - CLE

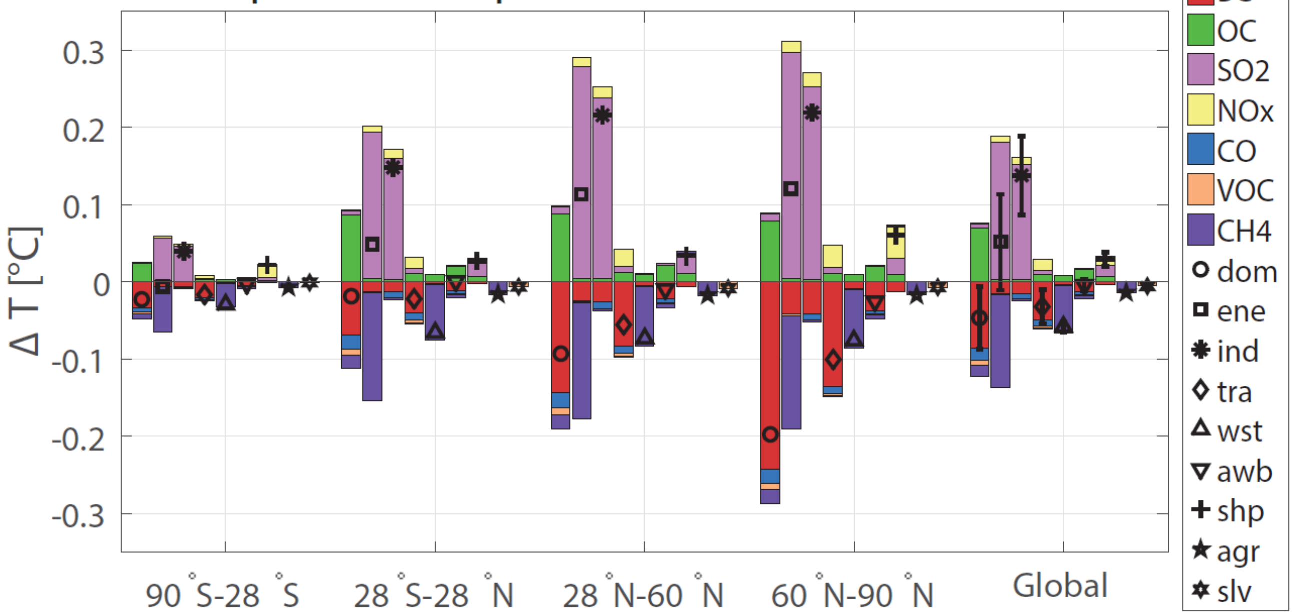


B) Temperature response in 2050, MTFR - CLE

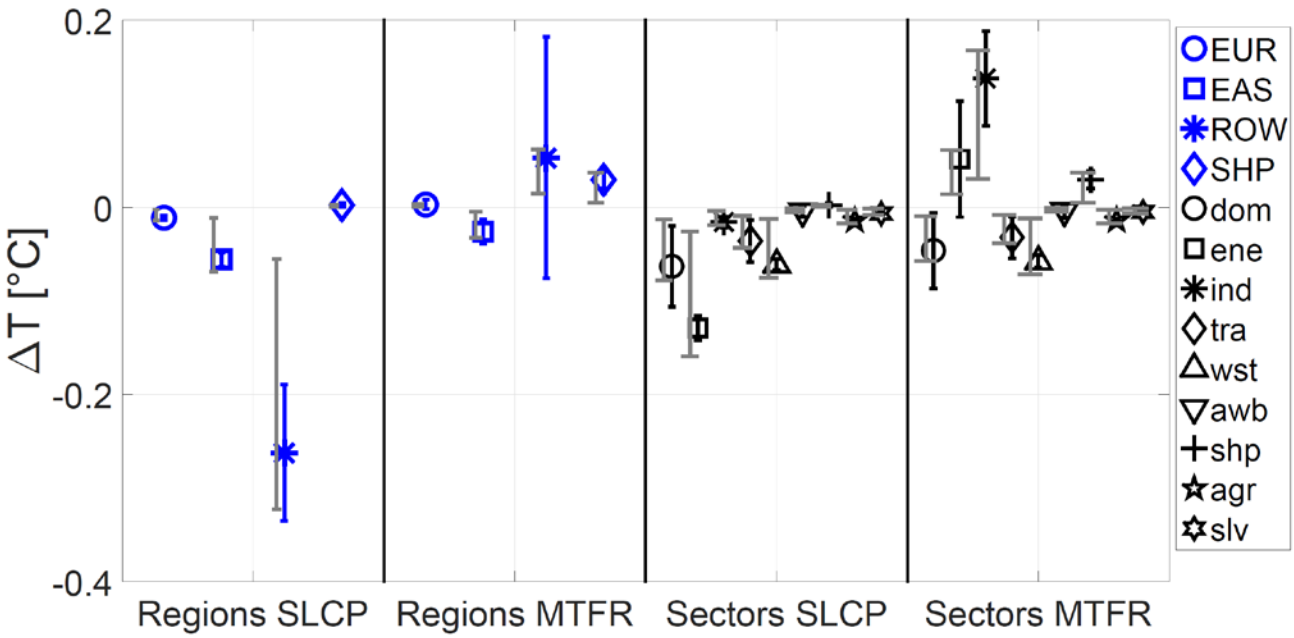




A) Temperature response in 2050, $\mathrm{SLCP_{\_scen}}$ - CLE



B) Temperature response in 2050, MTFR - CLE


0.2
0
-0.2
-0.4
ΔT [°C]
Regions SLCP
Regions MTFR
Sectors SLCP
Sectors MTFR
EUR
EAS
ROW
SHP
dom
ene
ind
tra
wst
awb
shp
agr
slv