Response to comments by anonymous referee #1 on “A continued role of Short-Lived Climate Forcers under the Shared Socioeconomic Pathways” by Lund et al.

We thank the referee for the detailed and thorough review of our paper, which has contributed to substantial improvements to our manuscript. Following the general comments and suggestions, we have repeated the analysis accounting for carbon-climate feedbacks and performed sensitivity tests to explore the impact of methodological choices, given in the supplementary material. We have also made substantial additions the Methods section, as well as changes to improve the flow of section 3.1. Responses to induvial comments are given below.

GENERAL COMMENTS

The manuscript makes an important contribution to the literature by providing a detailed assessment of SLCF emissions, implications of mitigation approaches, and understanding the implications for global temperature over different time horizons and under different SSPs. I have two major, related methodological concerns that I believe the authors need to address (but also should be able to address) for the paper to deliver on its promise. Both concern the use of AGTP and convolution of an IRF to derive outcomes over different time horizons and for emission pathways, and the fact that the exact methodology is too opaque yet choices here are critical.

My first concern is that a comparison should be shown (can be done in Supplementary Material) of how the IRF and AGTP used in this paper compares to the IPCC AR5 and body of literature used in the draft IPCC AR6 (the authors obviously can’t cite the IPCC AR6 draft, but it would be enormously helpful if their IRF and AGTP had a strong resemblance to what is coming out of the AR6 draft, because if it doesn’t, it clear is missing some important science point).

One important aspect of this is the treatment of climate-carbon cycle feedbacks. There is enough literature and recommendations in various papers arguing that this should be included, and the consequences are non-trivial for SLCFs especially for longer time horizons of 100 years – based on the AR5, this more than doubles the AGTP100 of methane. Since the goal of the paper is to describe the impact of SLCF emissions and mitigation over both short and long time horizons, the choice here is critical – but I’m not at all clear based on the current manuscript what choice was made.

I’d argue strongly that the authors should include a climate-carbon cycle feedback in their IRF – as not doing so would make the results for 100-year horizons, and for emission pathways (i.e. the effect of sustained SLCF emissions) misleading. Given the different lifetimes within SLCFs, this could also affect the ranking of different regions and sectors – it would not be a uniform scaling such as from the choice of ECS. So this really matters in my view for the validity of findings.

I would therefore ask the authors to (a) make fully transparent how their IRF and AGTP compares to IRF and AGTP that include climate-carbon cycle feedbacks from the IPCC AR5, and glancing at the studies and assumptions used in the AR6 draft, and (b) if their current IRF and AGTP does not include climate carbon cycle feedbacks or is missing some other critical aspects, to update their IRF and re-run their analysis. I’m hoping that this would be possible without requiring too much additional work since the framework for analysis should not change (and some results may not change either – which in itself would be a useful finding from this study!)

a) In the present analysis we do not report normalized metrics, have different geographical definitions than those used in IPCC AR5 (and other literature), and include various small updates compared to IPCC AR5 (e.g., radiative efficiencies calculated using Etminan et al. (2016) , which makes a direct comparison difficult. However, the reviewer raises a fair point as our results can readily be used to present new GTPs. To assess the order of magnitude difference that may arise from these methodological choices, we have repeated our AGTP calculations and pulse-based analysis using different combinations of carbon dioxide and climate response IRFs from the literature. A comparison of selected AGTP timeseries, as well as examples of how GTPs and temperature responses to individual species are affected, is presented in the supplementary material.

Specifically, we use the Joos et al. (2013) CO2 IRF with Boucher and Reddy (2008) (as in AR5), Gregory et al. (2013) (as in the rest of our study), and Gasser et al. (2017) temperature IRFs. Additionally, we add two runs where we compare results using the CO2 IRFs with and without carbon climate feedback from Gasser et al. (2017). The most notable differences arise from the switch from Boucher and Reddy (2008) IRF_T to Gregory et al. (2013) or Gasser et al. (2017). We $_{also}$ note that the sign of the difference (i.e., lower/higher values) depend on time horizon. The overall picture of our findings does not change, but the sensitivity analysis is a useful documentation.

Finally, the manuscript has been updated with more clear descriptions of methodological choices, including the use of Etminan et al. (2016) radiative efficiency equations, choice of IRFs and treatment of carbon-climate feedback (see below).

b) We thank the review for raising the point about climate-carbon cycle feedback (CCf). This is an important aspect but was neglected in our first calculations. We have now included the CCf using the framework developed by Gasser et al. (2017) with the OSCAR v2.2 simple earth system model, updating all figures and results. Since there are other approaches to accounting for CCf in the literature, we also provide AGTPs both with and without the CCf included in the data repository. As discussed in Gasser et al. (2017), the addition of a CCf term according to their approach increases the non-CO2 metrics, but less so than initially suggested by IPCC AR5 using the more simplified Collins et al. (2013) approach. This increase does not alter the overall picture and conclusions from our analysis. Nevertheless, the consistent treatment of CCf is a significant improvement to our paper.

My second concern is that their IRF and AGTP apparently does not include saturation effects arising from concentration changes (although it took me until the discussion on page 12 to realise this, which underscores my sense that the methodology is not transparent enough). The use of a linear AGTP is not acceptable in my view for the part of the paper that compares outcomes under different SSPs and mitigation targets. For some gases (methane as the biggest forcer included), their concentration differs markedly between the stringent and non-mitigation scenarios, which has a substantial effect on their radiative efficacy and hence contribution to warming over time. It is simply not defensible in my view to exclude this dependency but in a paper that seeks to evaluate the contribution to temperature from different gases under those different scenarios. Using a dynamically updated AGTP (i.e. adjusted based on concentration of each gas) could well change some of the results substantially (at least sufficiently to make the quantitative results questionable). Again, I think this is doable – it would not be hard to scale the AGTP based on the concentration of each gas and changing radiative efficacy, and re-run the analysis with such a dynamically updated AGTP. As for my other main comment, the framework for analysis would remain unchanged, and some or many key results may or may not change – which, again, would be a useful result in itself. All other comments are comparatively minor (though some include requests to broaden discussion or restructure some sections), as detailed below.

We thank the reviewer for this comment. (A similar one was raised by referee #2 – see response there as well.) For the well-mixed gases, adjusting radiative efficiency by background concentration is certainly possible. For CO_2, the dependence on emission/concentration scenarios is partly offset by/accounted for by the IRF, resulting in low scenario sensitivity (e.g., Caldeira and Kasting 1993; Aamaas et al. 2013). Due to lack of gridded scenario data, we do not include N_2O in our sector/region analysis. We have however, performed an additional set of calculations which includes the dependence of methane radiative efficiency. Calculations are done using global historical and future methane (and N2O, since Etminan et al. 2016 include the overlap of methane forcing with N2O) concentration from the IIASA SSP database. For the other (not well mixed) SLCFs considered, accounting for saturation effects is more complicated, involving spatially heterogeneous cloud and chemistry interactions, and would require simulations with (or results from) complex models. Such data is not readily available and beyond the scope of the present study, and would add a significant source of uncertainty. For consistency across components, all main results are shown without the changing radiative efficiency. The discussion on methane and saturation has been included in the discussion section with a figure in the SI.

SPECIFIC COMMENTS

L83: “increase” should come after “temperature”

Corrected.

L91: “complimentary” should be “complementary” (different meaning!)

Corrected.

L96: insert “sources and” before “mitigation strategies”

Added.

L98: “inexorably” is too strong: not all SLCFs are (especially HFCs, and methane not in all regions)

We agree that this wording was not optimal. Have modified to “many SLCFs are tightly linked to”

L112: insert “co-emitted” after encompass; also, I feel it is not correct to claim that sulfate aerosols have received considerably less attention so far – certainly in the 1990s that was the dominant aerosol included in climate studies. This should be clarified a bit and some of the older literature may well be highly relevant here (e.g. focus in the US on sulfate reduction from energy systems).

Added. And we see that this sentence does not fully recognize the scientific work. We have modified the sentence to clarify that we primarily refer to assessments by e.g., UNEP, CCAC and AMAP on SLCPs: “any assessment of the potential for alleviating climate warming by SLCF reductions should encompass co-emitted species such as sulfate, not only SLCPs.”

L117-121: I can’t agree with that generic claim: the SRES scenarios had a wide range of evolution of methane emissions, with significant continued increases in emissions especially in the A2 scenario but also A1FI. SSPs are more nuanced but there hasn’t been a material shift (unless you focus only on aerosols here – in which case, say so).

We thank the reviewer for pointing this out. We were indeed thinking primarily of aerosols and ozone precursors here. We have modified this paragraph for clarification:

“while previous scenarios for long-term evolution of aerosols and ozone precursor 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 projections of these emissions. Additionally, the SSPs provide a framework for combining future climate scenarios with socioeconomic development, and hence more detailed information about plausible future evolutions of society and natural systems. An up-to-date and detailed consideration of the emission composition is therefore timely and necessary for the design of (…)".

L160-191: As per my main comment, please expand this methodological section (possibly using SM) to demonstrate how the IRF and AGTP used in this paper compares to other IRFs. In particular, clarify whether longer-term warming contributions related to climate-carbon cycle feedbacks have been included (I argue strongly you should – tell us what the AGTP100 is for methane and HFC23). Also, add a comment here about how the AGTP adjusts over time in response to changing global GHG concentrations (again as per my main comments, I think it has to be changed dynamically to allow authors to derive conclusions about differences between SSPs/RCPs).
Please see response to general comments above. All AGTPs will also be made openly available via Figshare if the paper is accepted for publication. (Note that halocarbons are not included in this work, due to lack of available gridded and sectoral emissions data.)

L216: this section is not well structured in my view. It makes it hard to derive clear conclusions. I would suggest to improve on the structure by having one discussion about sectors, and another one about regions; also ensure you add a long-term (100 year) dimension, at present most of the discussion is for the near-term horizon.
We agree that this section could be cleaned up a it. We have made several changes to try to make it flow better. To better address the long-term dimension, we have added:
"In the long term, the net impact of AGR and WST is small, while energy is the largest individual contributor to warming due to its high CO_2 emissions (note that N_2O is not included in the present analysis as emissions are not included in the gridded CEDS and SSP database, but would add a small contribution to the long-term impact of AGR). The second largest driver of long-term temperature change is IND, demonstrating the importance of non-CO_2 emissions for shaping relative weight over different time frames."

L218-223: I can see the benefits of using 10 years, but I also struggle with the claim that this is "commonly used". Especially if the authors accept my main comment, that they need to re-do their analysis with a revised IRF/AGTP, I would urge you to consider a 20-year time horizon. The reason is that (a) this is in fact commonly used (GWP20), but also (b) that 20 years puts us very close to the time when temperatures should (begin to) peak in 1.5_C scenarios – so 20 years is much more policy relevant in my view than 10 years, which is really just the near-term rate of change.
We agree that the term "commonly used" only applies to 100 years and have removed this from the sentence. We believe, however, that there are compelling arguments for and benefits of using 10 years rather than 20 as near-term (e.g., 5 year global stock take cycle, EU 2030 emission targets, 20 years being very long from the point of many investors or sectors), as the referee also notes. We do, however, provide full time series of AGTPs to allow follow-up studies to adapt to their research questions. To make this even more clear, we have added to the existing discussion of time horizons. The paragraph now reads:
"Here we select 10- and 100-year time horizons to represent near- and long-term impacts. We recognize that other choices may affect the relative importance, and even sign, of the temperature response from some of the SLCFs like aerosols and NOx, or be more relevant for certain applications. For this reason, we provide the full time series of our AGTPs (see Data Availability)."

L226/227: add a bit of nuance here: the lifetime of SLCFs varies widely, with some causing warming for many decades (methane) whereas for others the bulk of warming is in the space of a few years.
Modified to "As the impact of the SLCFs decays over years to decades upon emission (…)"

L261-277: there's a bit of confusion about whether "mitigation potential" refers to the potential to reduce the emissions of a given SLCF, or to the potential for an intervention that might affect a range of SLCFs to reduce or increase temperature in the near or long term. These are very different aspects. I would reserve the word "mitigation" for anything that focuses on the reduction of emissions of a given species, and from there discuss the implications of such actions for temperature once changes in emissions of co-emitted species are taken into account over different time frames. Thanks for bringing this to our attention. We have made changes throughout the manuscript to be clearer and consistently use mitigation only for emission reductions, adopting the referee's suggestion.

L279: It would be really helpful if this section could clarify the scale of mitigation outcomes from SLCF mitigation compared to CO2 (and other long-lived GHG) mitigation. This would help keep the importance of SLCF mitigation in perspective, and allow the authors to use words such as "significant" with a lot more precise and justified meaning. If you only compare outcomes between SLCF mitigation approaches, but don't provide an overall scale (how much of the total mitigation in a given scenario comes from SLCFs, how much comes from CO2 and other LLGHGs), the paper could potentially be dancing on the head of a pin. You need to demonstrate how relevant this SLCF mitigation is in the bigger context (essentially a brief update from Shindell et al 2012).

Also, I feel this section needs to spell out in quite a bit more detail the assumptions behind each policy entry point and how this translates into quantified emission reductions. E.g. L285/286 says that P2 is about methane reductions, but then L305/306 seems to suggest that it can also be about CO2 reduction in the energy sector? Also more details are needed to understand the detailed emission reductions, and chemistry assumptions, for the agricultural mitigation scenarios (a lot of policies that target agricultural methane will affect agricultural N2O within farm systems). So I think the authors need to provide much more detail and quantification of how the broad policy principles in P1-P3 translate into mitigation of individual species for the different sectors. It's fine if there are subjective choices made – but we need to know what exactly those choices were to better understand to what extent the results are a function of those choices, or of the properties of the individual species that this paper helpfully aims to disentangle.
The purpose of this section is to demonstrate the applicability of our dataset for further studies of how mitigation measures and policy implementation – and, secondarily, the importance of co-emission. The policies, while based on feasible measures for the sectors, are simplified and emission reductions are based on expert judgement and literature. We have added more detail of policies and expanded Table 2 with detailed percentage reductions and footnotes. We have also clarified that results should be interpreted in light of their idealized and simplified nature. Moreover, with this in mind, we realize that it may be confusing to use the term "policy package", when we are in fact considering packages or combinations of idealized emission reductions. We now refer to "packages" only and discuss example measures. The section has been rewritten for clarification, also adding more about CO2 and longer-term effects.

In addition, we have added in the final paragraph of Sect. 3.1:
"Overall, the potential for global temperature reductions inherent in the present SLCF emissions is highly inhomogeneous, and co-emitted species – including CO_2 – must be taken into account in any targeted climate policy for reduction of near-term warming. We emphasize that mitigation of SLCFs, while important, need to be sustained and complimentary to strong cuts in CO_2 for long-term reduction in global warming."

L317: add "and mitigation targets" or something like this to the section heading, as the scenarios explored are not just the SSPs but the imposition of different mitigation targets on the SSPs (i.e. they are SSPs plus climate policy). Also clarify whether the way that the mitigation of SLCFs is then implemented follows the SPA protocol developed for mitigation modelling using SSPs (Kriegler E, Edmonds J, Hallegatte S et al (2014) A new scenario framework for climate change research: the concept of shared climate policy assumptions. Climatic Change 122(3): 401-414), since this could well affect how individual SLCF emissions change for different regions.
In order to avoid making the heading to long while still capturing this point, we have modified it to: "Temperature response to SLCFs and CO2 under the SSP-RCP scenarios".

Regarding the second point, we do not explicitly model future emissions or mitigation, but use the gridded data products available via ESGF by the IAMC and extract regional emissions using a geographical mask. We realize that it is insufficiently documented and have made some addition to the methods section to clarify (adding a reference to the section in the first paragraph of Sect. 3.3): "Historical emissions are from the CEDS database, while future emissions follow the SSP-RCP scenarios. Gridded and harmonized emissions are available for nine of the SSP-RCP combinations (Gidden et al., 2019), available via ESFG from the Integrated Assessment Modeling Community (IAMC). The gridded SSP-RCP data product, including the methodology for country and sector level emission mapping, is documented by Feng et al. (2020). Regional and sectoral emission scenarios are extracted using the geographical definitions and spatial mask from HTAP2 (Janssens-Maenhout et al., 2015)."

L324: I question the utility of using SSP5-8.5 for this paper. This scenario has value but by now is clearly counterfactual as far as emissions are concerned. This would not be a critical issue, but at the same time the paper is missing a much more relevant scenario such as SSP2-2.6, or SSP5-2.6. As it stands, the only stringent mitigation scenario is for an SSP1 world, which is only one of many worlds, understanding how SLCF emissions might evolve in a different socio-economic context but also stringent mitigation would be much more valuable than to take up space for the largely academic SSP5-8.5 scenario. So, my main concern is: add a stringent mitigation scenario (RCP2.6) using a different SSP (other than SSP1), otherwise this paper is missing a really important dimension. If you then keep the 8.5 scenario or drop it is in a way secondary.
We agree that there are other scenarios in the SSP-RCP framework that could tell a different story of SLCFs in the socioeconomic context. However, to our knowledge, the gridded and harmonized emission maps are only available for the nine CMIP6 SSP-RCP combinations, which only includes SSP1 stringent scenarios. Other scenarios may have become available recently but would be beyond the timeframe and resources available for this work to add. We think this comment may partly reflect our unclear description of methods, which we have now expanded (see response to comment above). We also slightly modify Sect. 3.3:
"In the following paragraphs, we show results from four of the nine SSP-RCP scenarios used in the present analysis (SSP1-1.9, SSP2-4.5, SSP3-7.0 and SSP5-8.5). Here we choose to show the scenarios that span the range of future emission evolutions, but recognize that the realism of SSP5-8.5 is debated in the literature due to its very high emissions (e.g., Ritchie & Dowlatabadi, 2017)."

L336/337: "we note that negative CO2 emissions are not included in these calculations": I'm puzzled by this. How can you evaluate SSP1-1.9 without negative emissions? Why not? This problem would only grow if the authors follow my advice to include SSP2 or SSP5-2.6.
Thanks for pointing this out. We see that this is unclear from the description of emissions and sectors, which is insufficient and only refer to Figure 1. Our primary objective is not to evaluate SSP1-1.9 in terms of absolute temperature impact, e.g., as has been done in the recent study by Torkaska et al. 2020 (see also discussion on limitations and interpretation of our method), but to quantify and compare the sectoral and regional mitigation potential and contribution to future temperature

impact depending on whether this mitigation is achieved or not. One reason for leaving negative CO2 emissions out of the analyses is that we consider it a mitigation measure, rather than a sector. From a practical point, attributing negative CO2 emissions to sectors (e.g., it would in part be energy, in part forestry) is not possible from the information available in the gridded SSP-RCP emission database for CMIP6 (which we rely on here, as has also been made more clear in the methods description), as these emissions are provided as a separate category. This would make the sector comparison less transparent across components. For actually evaluating the absolute temperature response under different SSP-RCPs, we agree that the negative emissions are essential. We have therefore included them in the dataset that will be made publicly available if the paper is accepted for publication. We have also made our scope and choice clearer in the text, adding:
"We note that since our primary focus here is on quantifying the contributions to, and potential for further reduction of, near- and long-term temperature impacts, we do not include negative CO_2 emissions which is already a mitigation measure. Furthermore, the gridded SSP-RCP emissions only provides a separate category for negative CO_2 and not information for mapping the emissions to economic sectors such as energy or forestry. We do, however, include the negative CO_2 category in our inventory of regional scenarios for further analyses beyond our study (see Data Availability)."

Tokarska, K. B., et al. (2020). "Past warming trend constrains future warming in CMIP6 models." Science Advances 6(12): eaaz9549.

L341/342: There seems to be a rather important finding buried here: are the authors saying that globally, energy contributed less to actual temperature change than agriculture and RES? If correct this might be worth highlighting more prominently to show how including SLCFs can change relevance over different time frames. Not that this should take away from the critical importance of mitigating CO2 from ENE, but it does seem a significant element. Another study that looked at warming attributable to livestock seems to go in a similar direction (Reisinger A, Clark H (2017) How much do direct livestock emissions actually contribute to global warming? Global Change Biology DOI: 10.1111/gcb.13975).
We thank the reviewer for pointing this out and making us aware of the reference. It is indeed an interesting point that methane and other reactive gases from agriculture has had a larger temperature impact than the net effect of the energy sector. This again points to the importance of methane, as well as the role of cooling contributions from the energy sectors. We have added the reference and the following:
"The relative importance of AGR and ENE historically is yet another example of how including SLCFs can change relevance over different time frames, as also demonstrated by Reisinger & Clark (2018) for non-CO2 livestock emissions. In this example, both the warming due to CH4 from agriculture and the contributions from cooling emissions in the energy sector act to shape the relative role of the sectors over time."

L376/377: I had to read this a few times to understand the "put another way" – might be worth rephrasing or disentangling a bit
We agree that this sentence is difficult to read. Moreover, it does not add really add anything to the conclusion, and we have removed it.

L378-390: again here, as for section 3.2, I would like to see a comparison with mitigation achieved by CO2 reductions, simply to avoid readers to take away misleading conclusions that somehow SLCFs are the dominant issue for climate change – I would say they are an important but second-order issue. Useful if the paper could state and substantiate this in some way. Also for L393-395: there is "much" to be gained – how much? Compared to how much from CO2?

The relative importance of CO_2 and non-CO_2 contributions between the scenario can be determined from Fig.4 (for regions) and Fig.S3 (previously S1 – for sectors). To place the magnitude of temperature differences in Fig. 5 in context we have added:
"Results are shown by region and sector, for all combinations where the temperature difference is greater than ±0.01°C. For comparison, the CMIP6 mean difference between SSP3-7.0 and SSP1-2.6 (which is close to 1.9 in emissions) in projected surface temperature when accounting for all global emissions is around 0.5 °C in 2050 and 2 °C in 2100 (Tokarska et al., 2020). As seen from Fig. 4 and Fig. S3, CO_2 is the key driver of this long-term temperature difference between the scenarios for most sectors and regions. However, as seen in Fig.5, there are also important SLCF contributions, most notably from the large sources of methane; agriculture, energy and waste management."

We have also made changes in several places to highlight that SLCF mitigation should only be complimentary to CO_2 reductions for long-term warming reductions.

L395-422: I find this section weak on actual policy, and inconsistent: for some sectors, authors mention specific interventions, whereas for agriculture, it just says "addressing agriculture emissions" – that's not a policy or intervention. Expand this to illustrate consistently what feasible interventions are for all sectors (including a brief flag for supply vs demand side interventions).
While we acknowledge the importance of understanding how to translate the potential for climate mitigation into actual emission cuts, a detailed and comprehensive assessment of the required policy strategies is beyond the scope of the present study, as is a description of the policies that underly the SSP-RCPs, which is covered in the studies documenting respective pathways. We have made some changes to this section to streamline (e.g., adding specific examples for agriculture methane reductions) and to clarify that we here outline general features and a few examples, we have added:
"While a comprehensive assessment of policy and technological interventions required to translate this potential to actual emission cuts is beyond the scope of the present study, we outline key general features and discuss specific examples in the case of methane, referring to existing literature for additional details, in the following paragraphs. "

L424-43: this is a useful thought experiment: how much warming would be avoided simply by improving technology for SLCFs (i.e. reducing emission factors consistent with SSP1), even in the absence of any dedicated climate policy (i.e. SSP3-7.0 vs SSP3-lowNTCF).
In line with the last comment, we have also emphasized the role of technological development more in the conclusions.

L449-480: please break this discussion into chunks – lots of different issues being discussed in a single mammoth paragraph. As flagged in main comments, using nondynamic AGTP to explore SSP/RCP pathways is a real problem that the authors have to address.
We have added a sub-heading 4.1 Caveats and uncertainties and separated the following discussion into clearer paragraphs. Following the addition of a sensitivity test for methane radiative efficiency adjusted by concentration pathways (see also comment above), we have also expanded the discussion.

L464-466: agricultural non-CO_2 emissions should be included in this list as they are also highly uncertain especially in developing regions (AFR, SEA, SAS).
We have added sentence to highlight that there are significant regional and sectoral differences in uncertainties in statistics and emissions:
"The level of uncertainty also differs across sectors, with emissions from nature related emissions (e.g., agriculture, landfills) more uncertain than technospheric emissions (e.g., in the fossil-fuel sector) , and regions (Amann et al., 2013; Jonas et al., 2019)."

L486: add that emission reductions of SLCFs have to be sustained to achieve longterm temperature change
We have removed the reference to long-term:
"(…) there is significant potential for additional reductions in near-term temperature change (…)"

L494-498: You could emphasise more strongly that this technological advancement brings benefits even if there is no dedicated climate policy addressing SLCFs, simply by reducing emission factors.
Yes, thank you, good point. Added.

Response to comments by anonymous referee #2 on "A continued role of Short-Lived Climate Forcers under the Shared Socioeconomic Pathways" by Lund et al.

We thank the referee for the detailed and thorough review, which has contributed to substantial improvements to our manuscript. Several steps have been taken to address the referee comments and concerns. Responses to individual comments are given below.

The manuscript emphasizes the importance of SLCF agents, especially for the short term impacts of climate scenarios, with some emphasis on methane. It is concluded that SLCFs continue to play a role in many regions. While it is important to reiterate this message, it is not so obvious what new findings are being presented. On several occasions, the results reinforce what is known, which does not justify publication.
The results for methane depend on methodological assumptions that are not transparent (e.g., emission categories) nor are they discussed in sufficient detail in the presentation of results. I found the discussion about the changing role of BC interesting, which could be highlighted more. I also recommend emphasizing regional differences more strongly. The finding that SLCFs are particularly relevant for low- and medium-income countries is relevant. In general, it would be good to deepen such analyses and bring new aspects forward more clearly.
There are some rather bold simplifications in the treatment of aerosols; e.g., it is not clear how the radiative properties of partially absorbing aerosols (with BC) are accounted for. They sensitively determine the radiative cooling efficiency. NOx is mentioned on several occasions, but its role is unclear. How is nitrate been included? It is semi-volatile and responds to changes in sulfate and ammonium. Has that been accounted for? This is particularly relevant for the comparison of scenarios.

The primary objective of this study is to provide a quantification the near- and long-term impact of individual species with a greater level of geographical and sectoral breakdown than previously existing in a unified framework, and to deliver a transparent and readily applicable data set of emission metric values for further use both in the scientific community and beyond to study the effectiveness and implications of emission changes following mitigation and policies implemented in at level of individual emission sources. We also provide the first (to our knowledge) breakdown of the SSP-RCP scenarios with this level of detail, highlighting regional evolutions that warrant further attention and work. Furthermore, following comments by referee #1 we now make a substantial methodological advancement by include the carbon-climate feedback. We have tried to make these points clearer throughout the manuscript. We have also rewritten section 3.1 to improve the flow and make the separate discussions about regions and sectors clearer, and made modifications to highlight the regional heterogeneity more clearly where possible.

In response to comments by both referees, the Methods section has been expanded to include more details about the underlying assumptions, and to guide readers outside the emission metric community. This includes e.g., specifications about AGTP for individual components and how they are treated within this concept, the choice of impulse response functions, references to the aerosol parameterizations and properties underlying the simulations of atmospheric concentrations and kernels, and emission inventories.

A relatively large temperature signal is expected from the indirect effects of aerosols on clouds, being highly non-linear especially at low pollution levels. I find the scaling by a factor of 2.1 to the impact of sulfate questionable. I recommend investigating (and showing) how sensitive the results are toward this assumption. There could be large regional differences.

We agree that this is a simplification, and this is also discussed in the manuscript (we have modified slightly to make it even clearer). However, information about the dependence of radiative efficiency of indirect aerosol effects on emission location is to our knowledge not readily available (spatial distributions of indirect RF are of course available but would not provide the type of information we need these are typically run using all emissions as input while aerosols can travel across distances and influence clouds beyond their source region). Moreover, because we scale the regional direct radiative efficiencies, a spatial dependence is in part accounted for in the resulting AGTP for a given region, under the assumption (and that is of course not well known) that there is a similar relative influence of geographical differences in local meteorology and dynamics on both direct and indirect aerosol effect. Aerosol indirect effect are uncertain and model dependent, which poses a general challenge for climate studies across modeling tools with different level of complexity – from ESMs to emulators. The overall uncertainty in RF may well be larger than any regional difference in the efficiency. We note that we do included an analysis of the spread in our results arising from uncertainties in forcing.

l.173 mentions a lack of information. Can't you get this from the chemistry-transport model?

Generally, offline chemistry transport models do not include aerosol-cloud interactions. An estimate of the indirect aerosol forcing can be derived with subsequent radiative transfer calculations (for the first indirect effect only) but is not available to us in the form of a radiative kernel which is the approach used here. A first order estimate of the radiative forcing due to aerosol-cloud interactions has been calculated for the total global emissions by Lund et al. (2019), but similar calculations to investigate the sensitivity of the forcing to emission location (i.e., RF per unit regional emission) has not been performed and does not, to our knowledge, exist in e.g., the bulk of HTAP2 literature.

l.175: The description of the -15% for BC after l.175 is unclear (e.g., the rapid adjustment). Can you explain?

To clarify, we have modified this paragraph, which now reads:

We also account for the semi-direct effect of BC (i.e., the rapid adjustments of the atmosphere to the local heating), which has been found to partly offset the positive direct radiative forcing (Samset & Myhre, 2015). Here we use the multi-model data of the ratio between semi-direct and direct BC RF from Stjern et al. (2017) and calculate an average adjustment factor to account for the influence of rapid adjustments of -15%. This is then applied to the AGTP of BC for all regions, except South Africa where Stjern et al. (2017) found a small positive forcing from rapid adjustments.

l.190: "lower than in the literature". By how much? By 0.885/1.06? Is the effect linear?

The difference depends also on the time scales of climate response IRF, and so the difference between AGTPs using different IRFs will have a temporal dependence as well. Following this comment and a comment by referee #1 we have performed a set of sensitivity simulations for the pulse based metrics using different combinations of IRF for the climate response and CO2 to show the order of magnitude impact of our methodological choice. A separate discussion with two new figures has been added to the supplementary material.

l.200: I am doubtful about the linearization of the temperature response by multiplying the emissions with the AGTPs. There are models available to compute this properly. This is particularly relevant for aerosols and ozone (the latter not being discussed at all), and to a lesser extent for methane, which has significant indirect effects, e.g., though ozone. Has this been accounted for?

We agree that there are non-linearities in the system that are not properly represented by the AGTP approach. We also agree that there are models (i.e. coupled chemistry-climate models) that can handle this better. The problem is that these models are not suited for running experiments to quantify impacts of specific (and thus small) emissions from specific sources (by region, sector and compound). And even the coupled models may not fully include the non-linear chemistry due to the coarse resolution of current climate models. So, the approach by the community is to build simpler models (e.g. FaIR, Smith et al., 2018).

There are two major steps in the cause-effect chain going from emissions to temperature change. First the relation between emissions and the effective radiative forcing, and then the relation between ERF and temperature change. For the relation emission ==> ERF we have performed an additional sensitivity test that where we include the non-linear effect of methane forcing efficiency, i.e., decreasing with increasing background levels of methane (see also response to comment by referee #1). For aerosols and ozone precursors we do account for the part of the non-linear effects of emissions taking place in different regions with differences in the physical climate (e.g., temperature, radiation and precipitation) by using simulations from the HTAP experiment to calculate the em ==> conc relation for 13 global regions and then a 4-D radiative kernel to get to the global ERF. This means that our AGTPs have different values for e.g. SO2 emissions in Europe vs. South Asia because the oxidation, transport processes and removal by precipitation is different.
The part of the non-linear effect caused by the changing background levels of the pollutants in the different emissions scenarios (e.g., saturation effects in ozone chemistry or cloud responses to increasing aerosols in a higher background pollution case) is less well quantified and is not included in our analysis.

For the relation ERF ==> global temperature change we use a standard two-term impulse-response function relating global mean ERF to global mean temperature change. This has been, and still is the standard approach, in simplified climate models (and the rational for using the GWP-metric). In coupled climate models there are indications that feedbacks (and thus climate sensitivity) are state-dependent, i.e. that the sensitivity increases as the Earth warms. However, at this point, this is still not fully understood and is not well quantified at intermediate warming levels as it diagnosed from 4xCO2 experiments of CMIP6.

Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., and Regayre, L. A.: FAIR v1.3: a simple emissions-based impulse response and carbon cycle model, Geosci. Model Dev., 11, 2273–2297, https://doi.org/10.5194/gmd-11-2273-2018, 2018.

l.210 Mentions ozone (also l.148), but it does not appear in the rest of the manuscript. It does not show in figures 2 and 3. Why has it not been included?
As per the established emission metrics framework, temperature responses are reported in terms of the emitted species, not the subsequent forcing mechanism. The ozone precursors include the impact of ozone and methane. In addition, we include nitrate aerosols, which is only recently becoming more common. In response to this and comments above, we have added a sentence in the methods after the AGTP equation to better clarify this point to readers outside the metrics community, referring the reader to the careful documentation existing in the previous literature: "Emissions of SLCFs can have both direct and indirect radiative effects. For BC, OC and SO2 we account for the direct, semi-direct and indirect RF as described below. AGTPs for NOx, CO and VOC includes the forcing due to tropospheric ozone production and (for NOx) nitrate aerosol formation, as well as the longer-term effect on methane lifetime and methane-induced ozone loss. The AGTP for methane includes the direct forcing, as well as the effect of OH-induced changes in its lifetime and adjustments to account for indirect effects on tropospheric ozone and stratospheric water vapor. See Aamaas et al. (2013) for details and AGTP equations for individual species."

l.241: There is much debate about CH4 emissions from the fossil fuel sector. What has been assumed in the calculations, and how does it compare with recent estimates? Methane is emphasized in the conclusions, but the attribution of emissions to sectors is not transparent. It would be interesting to deepen the discussion about the role of methane. Currently, the results are being reported but not really analyzed.

We thank the reviewer for raising this point. We use the historical, present-day and future emissions from the CEDS and SSP-RCPs inventories developed for CMIP6, and methane emissions follow the assumptions made there. From comments by both referees, we realize that the Methods discussion did not describe this very clearly and have expanded it. We also add a list of the sectors considered and their definition. While a comprehensive assessment of the influence that drive methane emissions is beyond the scope of this study, we have on several occasions added more details, following more specific comments by referee #1. The following new paragraphs have been included in the Methods section:

"Historical emissions are from the CEDS database, while future emissions follow the SSP-RCP scenarios. Gridded and harmonized emissions are available via ESFG from the Integrated Assessment Modeling Community (IAMC) for nine SSP-RCP combinations that form the core of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experiments (Gidden et al., 2019): SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP3-7.0 lowNTCF, SSP4-3.4, SSP4-6.0, SSP5-3.4, and SSP5-8.5. The gridded SSP-RCP data product, including the methodology for country and sector level emission mapping, is documented by Feng et al. (2020). Regional and sectoral emission scenarios are extracted using the geographical definitions and spatial mask from HTAP2 (Janssens-Maenhout et al., 2015).

We consider the energy (ENE), agriculture (AGR), waste (WST), residential (RES), industry plus solvents (IND), transport (TRA) and shipping (SHP) sectors, as they are defined in the harmonized CEDS-SSP emission inventory (Feng et al., 2020; Hoesly et al., 2018). Due to the large spread in historical estimates and lack of emissions consistent with CEDS, we do not include emissions due to land-use/land cover. Additionally, agricultural waste burning is excluded as these are more difficult to mitigate and estimates of future CO2 emissions are not available."

l.261: This is an interesting result that could be explained and emphasized more strongly.

We have expanded and added:

"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 measures that simultaneously affect both cooling and warming SLFCs are implemented, in turn also placing added focus on the need to reduce CO_2 in order to mitigation warming in both the near- and long-term. Such detailed characteristics at the emission source level are needed for the design of effective mitigation strategies."

l.364-366: This is interesting and could be explained and emphasized more strongly.

We have added:

"While previous decades have seen a southeastward shift in air pollution emissions, from high income regions at northern latitudes to East and South Asia, these findings suggest that a second shift may be underway, towards low- and middle-income countries in the developing world. Further studies are needed to improve the knowledge about the resulting climate and environmental consequences, as well as how to strengthen the mitigation options, in these regions."

l.443-445: This is interesting and could be explained and emphasized more strongly.

We have expanded the explanation and the section now reads:

"Secondly, as described in Sect.2, we use an AGTP for BC that is 15% lower than in previous studies using the same methodology. This is done to account for the rapid adjustments associated with BC short-wave absorption (Stjern et al., 2017), which has been found to reduce the effective RF in a range of global climate models via changes in stability and cloud formation (Smith et al., 2018). For our study, this factor applies to BC emissions from all sources and hence results in a reduced the net warming impact."

l.468-470: This is interesting and could be explained and emphasized more strongly.
While we agree that the recent CMIP6 results on ECS is interesting, we feel that a detailed discussion would distract from the core of the present study. We have added the reference to Zelinka et al. (2020) where the reasons for the difference in ECS estimates are discussed.

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

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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 highlight ~~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. 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. 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 SLCF mitigation ~~s~~ in strategies to reduce climate change~~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 assessments~~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 increase 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 comple~~i~~mentary to early and stringent CO_2 mitigation for the achievement of long-term climate goals (Ramanathan & Carmichael, 2008; 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 sources and mitigation strategies motivated by, and designed to address, different societal challenges. For instance, many SLCFs are tightly ~~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 SL~~F~~CF 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 (Hienola et al., 2018; Samset et al., 2018; Aamaas et al., 2019). Due to ~~the~~ co-emission, species such as sulfur dioxide (SO_2) are also commonly affected by measures to reduce climate warming even if these have~~climate mitigation policies that consider~~ LLGHGs as the~~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 strategy or assessment should encompass co-emitted species such as sulfate.~~, which have arguably received considerably less attentionso far.~~

A key characteristic of SLCFs is that the composition ~~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, w~~While previous scenarios for long-term evolution of aerosols and ozone precursor~~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 projections of these~~ed future~~ ~~SLCF~~ emissions. Additionally, the SSPs provide a framework for combining future climate scenarios (Representative Concentration Pathways – RCPs) with socioeconomic development, and hence more detailed information about plausible future evolutions of society and natural systems. ~~An u~~Up-to-date and detailed knowledge~~consideration~~ of ~~-~~the emission composition across individual sources 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, focusing on both added benefits and trade-offs offered by SLCF mitigation. ~~t~~Then we calculate ~~possible~~ the 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 SSP-RCP scenarios~~s~~. 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 detailed ~~comprehensive overview~~breakdown 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~~ demonstrating~~e~~ the potential for such applications ~~such use through calculations of the effect~~ for a set of idealized sectoral ~~policy~~ emission reduction 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 7 ~~the~~ sectors and 13 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.~~

2.1 Calculations of global and regional AGTPs

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 (Fuglestvedt et al., 2010; Shine et al., 2005; Aamaas et al., 2013); here we give a brief outline.

The ATGP gives the global-mean surface temperature response per kg species 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:

$$AGTP_i(H) = \int_{t=0}^{H} F_i(t) IRF_T(H-t)dt \qquad (1)$$

where F_i is the radiative efficiency. Emissions of SLCFs can have both direct and indirect radiative effects. For BC, OC and SO_2 we account for the direct, semi-direct and indirect RF as described below. AGTPs for NOx, CO and VOC includes the forcing due to tropospheric ozone production and (for NOx) nitrate aerosol formation, as well as the longer-term effect on methane lifetime and methane-induced ozone loss. The AGTP for methane includes the direct forcing, as well as the effect of OH-induced changes in its lifetime and adjustments to account for indirect effects on tropospheric ozone and stratospheric water vapor. See Aamaas et al. (2013) for details and analytical expressions for the AGTP of individual species. ~~and IRF is the impulse response function used to estimate the temperature response to a given radiative forcing.~~ ~~$IRF(t) = \lambda \sum_{j=1}^{J} \frac{c_j}{d_j} \exp\left(-\frac{t}{d_j}\right)$~~

~~See Aamaas et al. (2013) for further details about AGTP calculations for individual species.~~
For CO_2 and methane, we calculate ~~use~~ the global-mean *F* for year 2014 global concentrations (i.e., the year that is considered present-day in our emissions data – see below) using the equations from ~~from the IPCC Fifth Assessment report (AR5) (Myhre et al., 2013), adjusted for recent updates of the methane forcing~~ Etminan et al. (2016). Compared to the approach used on the IPCC Fifth Assessment report (AR5) (Myhre et al., 2013), this increases the radiative

efficiency of methane by 14%. -For NH_3, we use the IPCC AR5 best estimate for global mean radiative efficiency for all regions. For the remaining 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_i that depend on the location of the emission and calculate region-specific AGTPs for BC, OC, SO_2, and the ozone precursors. The~~se~~ regional radiative efficiencies (i.e., the global radiative forcing per unit of regional emissions) for BC, OC, sulfate, nitrate and ozone (in response to NOx, CO and VOC) are derived using radiative kernels (Samset & Myhre, 2011) and ~~from~~ atmospheric concentrations from simulations performed with the global chemistry transport model OsloCTM3 (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~~. Details about the chemistry, aerosol parameterizations, and assumptions for aerosol properties used to construct the kernels can be found in Lund et al. (2018) and Samset and Myhre (2011). In addition to their direct radiative effects, aerosols also affect the energy balance through modifications of clouds and atmospheric heating rates (indirect and semi-direct effects). -To account for the additional negative RF resulting from aerosol-cloud interactions ~~(or indirect aerosol effects)~~, we ~~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 about geographical dependence of the radiative efficiency, the same scaling factor is applied for all regions,~~,~~ recognizing that this is a simplification as ~~also the~~ the indirect effect also likely ~~may~~ var~~ies~~y with location of emission. We also account for the semi-direct effect of BC (i.e., the rapid adjustments of the atmosphere to the local heating ~~of BC which have been found to partly offset the positive direct radiative impact~~ (Smith et al., 2018)). Here we use the multi-model data of the ratio between semi-direct and direct BC RF from Stjern et al. (2017) and calculate an average adjustment factor for the rapid adjustments of -15%~~, by adjusting the AGTP of BC by -15% (based on Stjern et al. (2017), in~~. This is then applied to the AGTP of BC for all regions, except South Africa -where Stjern et al. (2017)~~except South Africa~~ found a small positive forcing from rapid adjustments. ~~, where the rapid adjustments were positive in that study. Ra~~Radiative forcing of BC deposition on snow and ice is not included in our estimates.

IRF_T in Eq.1 is the impulse response function used to estimate the temperature response to a given radiative forcing:

$$IRF_T(t) = \lambda \sum_{j=1}^{J} \frac{c_j}{d_j} \exp\left(-\frac{t}{d_j}\right) \qquad (2)$$

where c_j and d_j are constants and timescales of the fast and slow model of the climate system response, respectively, and λ is the equilibrium climate sensitivity (ECS).

An IRF is also used to represent the atmospheric decay of CO_2. Several different IRFs exist in the literature. Here we use the IRF_T from Geoffroy et al. (2013) (G13) and the IRF_{CO2} from Joos et al. (2013). ~~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:~~

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

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 G13Geoffroy et al. (2013) are given in Table 1. Compared to the IRF_T from Boucher and Reddy (2008) (B&R08) used in the bulk of previous metrics studies including IPCC AR5, G13 has shorter timescales and , which yields a lower n ECS of (0.885 K $(Wm^{-2})^{-1}$) compared to . This is somewhat lower than the ECS of 1.06 K $(Wm^{-2})^{-1}$) from B&R08. To place our values in the context of previous literature and explore sensitivities to the choice of IRFs, we perform additional calculations using different combinations of IRF_T and IRF_{CO2} – see section Sect. 1 of the Supplementary Information (SI). 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 somewhat shorter than the corresponding Boucher and Reddy (2008) numbers. Combined, this results in lower AGTPs values in the present study than previous literature.

Finally, we consistently account for the climate-carbon feedback (CCf) in the AGTPs. The IRF_{CO2}, derived from complex models, implicitly includes the CCf. However, this is not the case for other components. This inconsistency was first highlighted in Myhre et al. (2013), where a first attempt to include the CCf was made for halocarbons based on an earlier study by Collins et al. (2013). This method has since been refined. Here we use the framework developed by Gasser et al. (2017) where a separate IRF for the CCf was derived using the simple Earth system model OSCARv2.2. This IRF is used to calculate a $\Delta AGTP_i(H)$ which is then added to the $AGTP_i(H)$ without CCf. The difference between this method and the approach taken by Myhre et al. (2013) is discussed in Gasser et al. (2017). We also perform a sensitivity test to quantify the impact on our estimated temperature responses of excluding the CCf – see Sect. 4.1. Furthermore, as different methods to account for the CCf exist in the literature, we provide both sets of AGTPs for further use.

2.2 Emission data and temperature response calculations

As described above, we investigate the role and global temperature impacts of SLCF and CO_2 from two different perspectives. For each region and species, the First, the AGTPs at two given time horizons H (here 10 and 100 years)s are then multiplied by present-day (year 2014) emissions from the Community Emission Data System (CEDS) (Hoesly et al., 2018) for each species, sector and region. The result is the to calculate the temperature impact at a given time horizon H, $\Delta T(H$near- and long-term global temperature response, $\Delta T_i(H)$, to present-day regional and sectoral emissions.). In this study, H=10 years and H=100 years are selected to present near-term and long-term impacts, respectively.

Next, we quantify the temperature response to temporally evolving emissions from 1900 to 2100. 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(for each region and sector) given by:

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

Importantly, the AGTPs are linear in that they do not account for the potential changes in radiative efficiency with changing background pollution levels – see Sect. 4 for further discussion.

Historical emissions are from the CEDS database, while future emissions follow the SSP-RCP scenarios. Using this approach, we also calculate the global-mean temperature response to full time series of historical (CEDS) and future (the nine gGridded and harmonized SSPemissions are available via ESFG from the Integrated Assessment Modeling Community (IAMC) for nine SSP-RCP combinations that form the core of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experiments s (Gidden et al., 2019)) : SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP3-7.0 lowNTCF, SSP4-3.4, SSP4-6.0, SSP5-3.4, and SSP5-8.5. regional and sectoral emissions.The gridded SSP-RCP data product, including the methodology for country and sector level emission mapping, is documented by Feng et al. (2020). We extract regional emission scenarios using the geographical definitions and spatial mask from HTAP2 (Janssens-Maenhout et al., 2015). Furthermore, we consider the energy (ENE), agriculture (AGR), waste (WST), residential (RES), industry plus solvents (IND), transport (TRA) and shipping (SHP) sectors, as they are defined in the CEDS-SSP inventory (Feng et al., 2020; Hoesly et al., 2018). Due to the large spread in historical estimates and lack of emissions consistent with CEDS, we do not include CO_2 emissions due to land-use/land cover. Additionally, agricultural waste burning is excluded as these are more difficult to mitigate and estimates of future CO_2 emissions are not available.

2.3 Uncertainties

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 we here select ~~While the~~ 10- and 100-year time horizons ~~are commonly used~~ to represent near- and long-term impacts,~~ , w~~we recognize that other choices may affect the relative importance, and even sign, of the temperature response from some of the SLCFs~~ like aerosols and~~ ~~NOx,~~ or be more relevant for certain applications. For this reason, we also provide the full time series of our AGTPs (see Data Availability).

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). The total net effect after 10 years is therefore only slightly larger than that due to CO_2 alone. As the impact of the SLCFs decays ~~rapidly~~ over years to decades~~the first few decades~~ upon ~~after~~ emission, the total net ~~long-term~~ temperature impact after 100 years is predominantly determined by CO_2. As clearly seen in Fig. 2a, CO_2 emissions also cause a notable contribution to near-term warming. While both of these features are ~~While~~ well known in the scientific community, ~~-~~the~~is~~ role of CO_2 as ~~both~~ driver also of ~~a~~ near- ~~and long-~~term warming~~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 the mix of emissions ~~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, energy (ENE), agriculture (AGR), and waste management (WST) give the largest net near-term warming (i.e., after 10 years) ~~is estimated for the energy (ENE), agriculture (AGR), and waste management (WST) sectors~~ (Fig. 2b). For ~~The~~ AGR and WST, this is a result of ~~sectors are primarily a source of~~ strong 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), as well as CO_2, 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 the net effect on global temperature ~~benefits~~ of SLCF mitigation may be small in the case of the ~~from reductions~~energy sector if ~~may be offset if accompanied by~~ simultaneous reductions in SO_2 take place ~~in some cases~~. A particular feature of the energy sector, however, is that a significant portion of methane mitigation from oil and gas (production and distribution) ~~(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 g~~Global ~~level,~~ emissions from industry (IND) and shipping (SHP) cause a ~~small~~ net cooling impact despite a considerable warming from CO_2 emissions. In the long term, the net impact of AGR and WST is small, while energy is the largest individual contributor to warming due to its high CO_2 emissions (note that N_2O is not included in the present analysis as emissions are not included in the gridded CEDS and SSP database, but would add a small contribution to the long-term impact of AGR). The second largest driver of long-term temperature change is IND, demonstrating the importance of non-CO_2 emissions for shaping relative weight over different time frames. Aviation is not included here, but was recently evaluated by ~~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 regional 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) (Fig.2c). 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 should not be reduced~~tions measures should not be implemented~~, but that the net benefits on global temperature may be low~~er than expected~~ if ~~mitigation policies~~mitigation measures that -simultaneously affect both cooling and warming SLFCs are implemented, in turn placing added focus on the need to reduce CO_2 in order to mitigate warming in both the near- and long-term. In SEA, SAF and South and Central America (SAM and MCA) ~~emissions of~~ methane and BC emissions are presently high while emissions of CO_2 and cooling aerosols ~~emissions~~ are low compared to other regions, ~~. This~~ resulting~~s~~ in a net warming impact after 10 years that is substantially higher than that of CO_2 alone. This, in turn, suggest that using SLCF emission reduction to limit near-term warming would be more effective here than in many other regions. ~~Combined with low cooling contributions, this suggests that there is a higher potential for mitigation by targeting only SLCF emissions in these regions.~~ Such detailed characteristics at the emission source level are needed for the design of effective mitigation strategies.

Breaking the temperature impacts further down into economic sectors within each region (see “Data Availability” for numbers), we find that the results largely mirror the relative role of species and sectors on the global level shown in Fig. 2b. ~~As in the global case, the~~The warming contributions in South America and Africa, and hence ~~-~~higher potential for net temperature reductions, stem~~s~~ primarily from ~~methane from~~ the agriculture, ~~and~~ waste management~~ sectors~~, and ~~with additional potential in the~~ energy production sector~~s especially in MCA (see “Data Availability” for sectoral data within each region)~~. In SAF, mitigation of BC emissions ~~of BC~~ from the residential and transport sectors also play an important role. ~~In contrast,~~ In most regions, emissions from IND ~~the industry sector in most regions~~ cause a net negative impact on global temperature change, while in the ENE sector, impacts of ~~. The energy sector is characterized by competing~~ cooling and warming SLFCs~~SLCFs,~~ compete and warming from ~~leaving~~ CO_2 is a key driver of both ~~as the primary driver of net~~ near- and long-term warming~~term warming when considering the sector as a whole, i.e., without accounting for production and combustion sub-categories as discussed above~~.

Overall, the potential for global temperature reductions inherent in the present SLCF emissions is highly inhomogeneous, and co-emitted species – including CO_2 – must be taken into account in any targeted climate policy for reduction of near-term warming. We emphasize that mitigation of SLCFs, while important, need to be sustained and complimentary to strong cuts in CO_2 for long-term reduction in global warming.

3.2 Temperature response to exampleTemperature response to idealized policy cases mitigation measures 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 demonstrate the applicability of how our dataset may be used furtherwithout further use of complex models, we now calculate the effect on global temperature in the near- and long-term of emission changes following simplified exampless of emission reduction packages in polices in three of the global sectors (ENE, AGR and SHP). The measures policies are broadly assumed to be motivated by either *i)* air quality improvements (packagepolicy 1, P1), *ii)* methane reductions (as part of the SDG agenda or climate mitigation) (P2) or *iii)* CO_2 reductions/climate targets (P3). Table 2 shows the set of species reduced in each case, each resulting in a different package of emission reductions (Table 2),, with the percentage reduction given in parentheses. We note that these reductions are based on expert judgement given underlying assumptions, e.g., for the reduction in shipping speed, and are associated with uncertainties. Furthermore, they are assumed to occur instantaneously. However, as the primary but linearly purpose here is illustrative, the examples are kept idealized and should be interpreted as such.

The global temperature effect resulting from elimination of these emissions in each package afteron 10 and 100 years time horizons 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 set of measurespolicy (P1), e.g., implementing end-of-pipe measures such as scrubbers, filters and catalysts, could therefore be implemented that would strongly reduce SO_2 and NOx emissions but would not noticeably affect the- key methane or CO_2 contribution. Such measures are well understood, i.e., their efficiencies, costs, and technical implementation has been well documented and real-life application is already widespread but there is still large potential, especially in fast-growing economies. As shown by the top bar on the left in Fig.3, the subsequent near-term temperature impact would be a warming contribution due to removal of cooling aerosols, adding to the already large net warming impact of the sector (of methane Fig. 2b)for the sector as a whole. As seen from the right-hand side of Fig. 3, the long-term effect would also be minor, leaving the dominating CO_2 warming. A significant fraction of methane emissions, originating from the production and distributionstage of fossil fuels, could be mitigated separately from several most other SLCFs, for instance by addressing venting and leaks from oil, gas and coal exploration, and upstream and downstream gas flaring. Respective measures would include capture/recovery and use of gas, as well as reduced and improved flaring, with added benefits in terms of reduced CO_2 and/or BC (P2, P3). This , resultsing in a notable reduction in both the near- and long-term impact of the sector~~r~~. Finally, P3 shows the impact of a dedicated climate strategy, here illustrated by the change in emissions ~~(Klimont et al., 2017)~~between a middle-of-the-road and a below-two-degrees scenario (in 2050, obtained from the GAINS model (Klimont et al., 2017)), where more substantial CO_2 mitigation also result in larger reduction of the sector's long-term temperature impact than in P2.

Due to the dominating contribution from methane to the temperature impact of ~~Similarly, policies for~~ the agriculture sector, measures that primarily target other emissions, such as improving nitrogen use efficiency (P1), unsurprisingly bring low net climate benefits unless accompanied by simultaneous measures for methane reductions (P2). Examples of the latter is promoting dietary changes, leading to lower meat consumption and consequently lower livestock numbers. Reducing NH_3 and NO_x (P1) could, however, bring important local air quality benefits, and our results suggest that these would come with relatively small trade-offs from unmasking of aerosol cooling, at least in terms of global mean temperature on this time scale~~ 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~~. Only small additional benefits (at a global scale) were estimated for the increased use of biogas that would result in reduction of both air pollutants and greenhouse gases (P3) due to utilization of livestock manures.

The net impact of the shipping sector (SHP) is a cooling in the near-term, as~~which has been~~ shown in several previous studies (e.g., Berntsen & Fuglestvedt, 2008; Fuglestvedt et al., 2009). Measures~~Policies~~ that eliminate~~reduce~~ shipping emissions of SO_2 (low sulfur fuels, scrubbers) and NOx (selective catalytic reduction) ~~(P1)~~ hence result in an added near-term warming, also when simultaneous elimination of the sector's CO_2 emissions occur (P2, P3). ~~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 and illustrative, and ~~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 pulse-based~~the~~ temperature impacts following ~~a pulse of emissions, i.e., assuming that the policies~~ instantaneous emission reductions~~ly affect the sectoral emission composition,~~. However, ~~-~~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), giving our dataset ~~allowing for a~~ broad applicability for ~~potential for~~ further studies ~~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~~ Temperature response to SLCFs~~s~~ and CO_2 ~~to global temperature change~~ under the SSP-RCP scenarios

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 SSP-RCP scenarios~~s~~ (Sect. 2.2). In the following paragraphs, we show~~focus on~~ results from four of the nine SSP-RCP scenarios used in the present analysis~~s~~ (SSP1-1.9, SSP2-4.5, SSP3-7.0 and SSP5-8.5). Here we choose to show the scenarios that span the range of future emission evolutions, but recognize that the realism of SSP5-8.5 is debated in the literature due to its very high emissions (e.g., Ritchie & Dowlatabadi, 2017). ~~that span the range of future emission evolutions.~~ See "Data Availability" for results from remaining five scenarios.

Figure 4 shows the evolution of temperature response under the SSP-RCPs for our source regions, with corresponding results for the global economic sectors given in Fig. S3~~1~~.

Our emissions regions not only have large differences in terms of present-day emissions, but also of~~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. This shows a projected shift in emissions and increasing importance of the developing world. We note that since our primary focus here is on quantifying the contributions to, and potential for further reduction of, near- and long-term temperature impacts, we do not include negative CO_2 emissions which is already a mitigation measure. Furthermore, the gridded SSP-RCP emissions only provides a separate category for negative CO_2 and not information for mapping the emissions to economic sectors such as energy or forestry. We do, however, include the negative CO_2 category in our inventory of regional scenarios for further analyses beyond our study (see Data Availability).

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), upon which ~~and~~ ENE remains the largest individual sector until 2100 in all scenarios. The relative importance of AGR and ENE historically is yet another example of how including SLCFs can change relevance over different time frames, as also demonstrated by Reisinger and Clark (2018) for non-CO_2 livestock emissions. In our results, both the warming due to CH_4 from AGR and the contributions from cooling emissions from ENE act to shape the relative role of the two sectors over time. 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 in~~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. S42 for remaining regions and Fig.S13b for breakdown by global sector.

The SSP-RCPs 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 previous decades have seen a southeastward shift in air pollution emissions, from high income regions at northern latitudes to East and South Asia, these findings suggest that a second shift may be underway, towards low- and middle-income countries in the developing world. Further studies are needed to improve the knowledge about the resulting climate and environmental consequences, as well as how to strengthen the mitigation options, in these regions. 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 still assumes strong air air pollution control since the high use of fossil fuels would otherwise result in unbearable air 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 future temperature response is between SSP1-1.9 and SSP3-7.0. To see where the largest additional climatic benefit can be gained from mitigating SLCF emissions in line with SSP1-1.9, relative to 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. For comparison, the CMIP6 mean difference in projected surface temperature between SSP3-7.0 and SSP1-2.6 (which is close to SSP1-1.9 in emissions) is around 0.5 °C in 2050 and 2 °C in 2100 when accounting for all global emissions (Tokarska et al., 2020). As seen from Fig. 4 and Fig. S3, CO_2 is the key driver of this long-term temperature difference between the scenarios for most sectors and regions. However, as seen in Fig.5, there are also important SLCF contributions, most notably from ~~Our results emphasize the importance, for both near- and long-term climate change, of~~ the largest~~strong~~ sources of methane; agriculture, energy and waste management. Furthermore, 9 of the 12 top contributions are from regions ~~especially~~ in Africa, South Asia or~~and~~ South and Central America, again demonstrating the importance of the development in low- and middle-income countries for future levels of SLCFs. ~~.~~ Fig.5. also shows how the strong SLCF mitigation in SSP1-1.9, relative to SSP3-7.0, can result~~s~~ in a net warming contribution to climate for some region-sector combinations, as exemplified by ~~such as~~ the industry sector 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. While a comprehensive assessment of policy and technological interventions required to translate this potential to actual emission cuts is beyond the scope of the present study, we outline key general features and discuss specific examples in the case of methane, in the following. Available literature suggest that ~~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. As demonstrated by our findings, ~~F~~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 sectors. The rapidly industrializing and developing countries would need to further strengthen legislation for the power, industry, transport sectors, implement improved measures to ~~introduce new laws to improve~~ reduce waste management emissions, reduce emissions from agriculture, and provide wide access to clean fuels securing cooking and heating needs. Several of these policies would contribute positively to the~~secure achievements of~~ SDGs~~ goals~~ (Rafaj et al., 2018). For methane, the non-CO_2 component found here to be most important for future warming, reducing venting and increasing utilization of associated petroleum gas in oil and gas exploration and ~~,~~ 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). Integrated response options that can deliver significant mitigation also exist for the agriculture sector, including increased productivity of land used for food production and improved livestock management (Smith et al., 2019). ~~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 strength(Zelinka et al., 2020)en 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, ~~A similar suite of methane measures is needed as for the developed and developing world, although waste management requires larger transformation and there is additional significant potential to reduce emissions from coal mining sector in the latter. 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. Specific measures for reducing aerosols and ozone precursors in order to improve~~ing~~ air quality while contributing to climate change mitigation have recently been assessed for South East Asia (UNEP, 2019) and Latin America (UNEP, 2018). As shown in the present analysis, contributions from SLCFs to temperature change are projected to increase strongly in the Middle East and Africa in several scenarios. ~~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). This underlines the ~~, highlighting the ~~need for further focus on these~~is~~ regions in future studies and assessments.

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 than~~compared t~~ in~~o~~ SSP3-7.0.

The potential for reducing near-term warming ~~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~~effectively removing BC. By now these vehicles represent a significant part of the fleet in many regions and the trend is expected to continue. Secondly, as described in Sect.2, we use an AGTP for BC that is 15% lower than in previous studies using the same methodology. This is done to ~~by~~ account~~ing~~ for the rapid adjustments associated with BC short-wave absorption (Stjern et al., 2017), which has been found to reduce the effective RF in a range of global climate models via changes in stability and cloud formation (Smith et al., 2018). For our study, this factor applies to BC emissions from all sources and hence results in a ~~r~~reduced~~s~~ the net warming ~~climate impact of the aerosols, we estimate a lower temperature response than earlier~~ impact. ~~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.

4.1 Caveats and uncertainties

The AGTP is a well-established framework that has been applied in several studies of attribution of temperature impacts to emission sources and scenarios (e.g., Collins et al., 2013; Lund et al., 2017; Sand et al., 2015; Stohl et al., 2015; Aamaas et al., 2019). ~~Gasser et al. (2017); Myhre et al. (2013)~~Here we have also consistently included the carbon-climate feedback in the AGTP for all species. This increases the non-CO_2 AGTPs, however, less than initially suggested by Myhre et al. (2013) as discussed by Gasser et al. (2017). Figure S5 shows the global mean net temperature response to total emissions under 6 of the 9 SSP-RCPs, with and without the feedback. By the end of century, there is a 5-9% difference depending on scenario.

A key strength of the AGTP framework is that ~~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, in a transparent manner. However, ~~but also~~ there are also~~introduces~~ caveats. Importantly, the AGTP metric is linear, while in reality the ~~and does not include saturation effects~~ radiative efficiency can have non-linear dependencies on the background atmospheric conditions~~as emissions and atmospheric concentrations increase.~~. In this study, ~~we~~ we account for one part such non-linearities by using radiative efficiencies for the aerosols and ozone precursors that vary with emission location to calculate region-specific AGTPs. The part of the non-linearities caused by changing background levels of pollutants ~~in the regions~~ is, however, not included. ~~This is an is an additional source of uncertainty for the SLCFs. For aerosols and ozone precursors, potential saturation effects involve complex, spatially heterogeneous chemistry, cloud and climate interactions that require detailed chemistry-climate simulations to resolve, and even then, may not be fully captured due to e.g., the coarse resolution of current climate models.~~ For the well-mixed greenhouse gases CO_2, CH_4 and N_2O, the radiative efficiency (RE) ~~(RE)~~ is reduced with increasing atmospheric background concentrations ~~(REF)~~. Previous literature suggests that ~~the AGTP of~~ the sensitivity to ~~CO_2 is largely insensitive to~~ emission scenario is small, and the relationship between emissions and temperature response more linear, for CO_2 ~~as the difference in RE is partly compensated through the IRF (REFs)~~(Caldeira & Kasting, 1993). However, the same has not been shown for methane (and N_2O – which is not considered here)~~, the changing RE is more important for the AGTP and resulting temperature response~~. ~~Here w~~We therefore perform an additional sensitivity test ~~for methane, w~~where we use the ~~calculate~~ RE of methane ~~(using the equation~~

from (Etminan et al., 2016) adjusted to global atmospheric concentrationsused to calculate the AGTP is adjusted to the global atmospheric concentrations over time (using the equation from Etminan et al. (2016) that also account for the overlap with N_2O, and global concentrations for each SSP-RCP from the IIASA SSP database (IIASA, 2020; Riahi et al., 2017)). Figure S5 shows the resulting temperature response, compared to the temperature response calculated with and without the CCf. As expected, using a dynamically adjusted RE results in a lower warming in the high emission scenarios and a slightly higher temperature response under low emissions. In the case of extreme scenario SSP5-8.5, the effect is of the same order of magnitude as that from adding the CCf, but of opposite sign. For aerosols and ozone precursors, potential saturation effects involve complex, spatially heterogeneous chemistry, cloud and climate interactions that require detailed chemistry-climate simulations to be resolved, and even then, may not be fully captured due to e.g., the coarse resolution of current models. We emphasize that the absolute magnitude of temperature changes quantified with the AGTP framework should be interpreted with care, as this method is primarily designed to study relative importance and relationships between individual emissions and sources.

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 to the extent possible, but results have considerable uncertainty, in emissions, RF and climate sensitivity. As shown in Fig. 2a, we estimate, due to uncertainty in RF alone, 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). The level of uncertainty also differs across regions and sectors, with emissions from nature related emissions (e.g., agriculture, landfills) more uncertain than emissions in the fossil-fuel sector (Amann et al., 2013; Jonas et al., 2019). 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 equilibrium climate sensitivity (ECS) inherent in the climate response in IRFimpulse response function (IRF) used in the present analysis is yields an equilibrium climate sensitivity (ECS) of 0.885 K $(Wm^{-2})^{-1}$. This is , which is in the upper range reported by Bindoff et al. (2013), but lower than many recent estimates (Forster et al., 2019; Zelinka et al., 2020). While emissions uncertainties have a strong the former has a spatiotemporal characterdependence, changes in the ECS mostly act to scale estimates for all sectors and regions but is less important for their relative ranking.

Furthermore, oOur 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. Using the concept of Absolute Global Temperature change Potential (AGTP), an emission metric-based emulator of the climate response, we here investigate the contribution of emissions of SLCFs and CO_2 from 7 economic sectors in 13 source regions to global temperature change. In addition to quantifying the near- and long-term temperature response to present-day emissions, i.e., in line with the traditional emission metric studies, we evaluate the role of individual SLCFs and CO_2 as projected by the most recent generation scenarios, the Shared Socioeconomic Pathways (SSPs), with greater regional and sectoral detail than previous literature. We account for the geographical dependence of the radiative forcing of SLCF emissions, as well as the current understanding of global-scale indirect and semi-direct aerosol forcing. A key update to our method relative to the bulk of comparable literature, is the inclusion of a treatment of the carbon-climate feedback in the AGTPs of the SLCFs.

~~Here we~~As is well established, CO_2 is the dominant driver of warming on longer time scales and any strategy for limiting long-term temperature change critically depends on deep cuts in CO_2 emission. As shown by our results, CO_2 also give a significant contribution to near-term warming. The potential for additional reductions in near-term temperature change from reductions in present-day SLCF emissions is highly inhomogeneous across region and sector. ~~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.~~ Key in all regions are the ~~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, some sectors and regions, notably industry, energy and transport in East and South Asia and the Middle East, have strong contributions from cooling SLCFs resulting in a net negative near-term temperature impact or an approximate balance between cooling and warming SLCFs. While this does not imply that mitigation measures should not be implemented, understanding of the detailed characteristics and relevance over time at the emission source level is needed for the design and assessment of mitigation strategies.

~~In contrast to the existing potential, we find that~~ The regional heterogeneity in SLCF~~s~~ emissions and subsequent contributions to global temperature change continues under most of the nine SSP-RCP scenarios considered here. While CO_2 becomes the dominant contributor to warming in all regions over time, SLCFs are projected to continue to play an important role for global temperature change over the 21st century in many regions~~under most of the Shared Socioeconomic Pathway (SSP) scenarios~~. In particular, emissions of SLCFs in East and South Asia is projected to remain high, at least until the mid-21st century. Moreover, there is a shift in emissions towards low- and middle-income countries in the developing world. –Notably, ~~Several of the SSPs project~~ a ~~particularly~~ strong increase in emissions in Africa south of the Sahara is projected under most of the SSP-RCPs considered, and is especially pronounced in SSP3-7.0 and SSP5-8.5. Hence, ~~I~~in addition to the ~~the~~ focus on the current ~~South and East Asia as the~~ major current sources of SLCFs, enabling technological and legislative development ~~and legislation implementation~~ on the African continent will likely ~~may~~ be of key importance for a transition from high emission pathways ~~air pollution SSP3-7.0 pathway~~ towards one in line with SSP1-1.9 and the ambitions of the Paris Agreement, which in turn c~~w~~ould give ~~add~~ reductions in global warming already over the next couple of decades. Technological advancement could bring benefits even if there is no dedicated climate policy addressing SLCFs, simply by reduced emission factors.

The large spatiotemporal heterogeneity in emissions trends and subsequent temperature responses underlines the need to go beyond global emission scenarios. By quantifying ~~assessing~~ the global temperature response to emissions from 13 regions, 7 sectors and 9~~4~~ scenarios in a consistent and transparent framework, we provide a more comprehensive dataset than, to our knowledge, currently exists. We note that the AGTP framework is primarily designed to study relative importance and relationships between individual emissions and sources, and that the absolute magnitude of temperature responses should be interpreted with care due to its linear nature. The uncertainties in emissions could also affect the regional and sectoral ranking but are poorly known. However, by making our full dataset publicly available, we provide a tool that ~~,~~ enabl~~ing~~es further analysis and comparison of e.g., mitigation strategies at the sectoral and regional level ~~and economic analyses~~ without the use of complex models. ~~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.

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References

Allen R. J., Turnock S., Nabat P., et al., *Atmos. Chem. Phys. Discuss.* 2020, 1-30, 10.5194/acp-2019-1209, 2020.

Amann M., Klimont Z. & Wagner F., *Annual Review of Environment and Resources.* 38(1), 31-55, 10.1146/annurev-environ-052912-173303, 2013.

AMAP, 2015.

Anenberg S. C., Schwartz J., Shindell D., et al., *Environmental Health Perspectives.* 120(6), 831-839, doi:10.1289/ehp.1104301, 2012.

Arneth A., Unger N., Kulmala M., et al., *Science.* 326(5953), 672-673, 10.1126/science.1181568, 2009.

Berntsen T. & Fuglestvedt J., *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., et al., 2013.

Bond T. C., Doherty S. J., Fahey D. W., et al., *Journal of Geophysical Research: Atmospheres.* 118(11), 5380-5552, 10.1002/jgrd.50171, 2013.

Boucher O. & Reddy M. S., *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., et al., *Nature Climate Change.* 3, 1021, 10.1038/nclimate2034, 2013.

Caldeira K. & Kasting J. F., *Nature.* 366(6452), 251-253, 10.1038/366251a0, 1993.

CCAC, 2019.

Collins W. J., Fry M. M., Yu H., et al., *Atmos. Chem. Phys.* 13(5), 2471-2485, 10.5194/acp-13-2471-2013, 2013.

Crippa M., Janssens-Maenhout G., Dentener F., et al., *Atmos. Chem. Phys.* 16(6), 3825-3841, 10.5194/acp-16-3825-2016, 2016.

Etminan M., Myhre G., Highwood E. J., et al., *Geophysical Research Letters.* 43(24), 12,614-612,623, 10.1002/2016gl071930, 2016.

Feng L., Smith S. J., Braun C., et al., *Geosci. Model Dev.* 13(2), 461-482, 10.5194/gmd-13-461-2020, 2020.

Forster P. M., Maycock A. C., McKenna C. M., et al., *Nature Climate Change*, 10.1038/s41558-019-0660-0, 2019.

Fuglestvedt J., Berntsen T., Eyring V., et al., *Environmental Science & Technology.* 43(24), 9057-9062, 10.1021/es901944r, 2009.

Fuglestvedt J. S., Shine K. P., Berntsen T., et al., *Atmospheric Environment.* 44(37), 4648-4677, https://doi.org/10.1016/j.atmosenv.2009.04.044, 2010.

Gasser T., Peters G. P., Fuglestvedt J. S., et al., *Earth Syst. Dynam.* 8(2), 235-253, 10.5194/esd-8-235-2017, 2017.

Geoffroy O., Saint-Martin D., Olivié D. J. L., et al., *Journal of Climate.* 26(6), 1841-1857, 10.1175/jcli-d-12-00195.1, 2013.

Gidden M. J., Riahi K., Smith S. J., et al., *Geosci. Model Dev.* 12(4), 1443-1475, 10.5194/gmd-12-1443-2019, 2019.

Haines A., Amann M., Borgford-Parnell N., et al., *Nature Climate Change.* 7(12), 863-869, 10.1038/s41558-017-0012-x, 2017.

Harmsen M., Fricko O., Hilaire J., et al., *Climatic Change*, 10.1007/s10584-019-02436-3, 2019.

Hienola A., Partanen A.-I., Pietikäinen J.-P., et al., *Environmental Research Letters.* 13(4), 044011, 10.1088/1748-9326/aab1b2, 2018.

Hmiel B., Petrenko V. V., Dyonisius M. N., et al., *Nature.* 578(7795), 409-412, 10.1038/s41586-020-1991-8, 2020.

Hoesly R. M., Smith S. J., Feng L., et al., *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., et al., *Environmental Research Communications.* 2(2), 025004, 10.1088/2515-7620/ab7457, 2020.

Höhne N., Blum H., Fuglestvedt J., et al., *Climatic Change.* 106(3), 359-391, 10.1007/s10584-010-9930-6, 2011.

IIASA, 2020.

Janssens-Maenhout G., Crippa M., Guizzardi D., et al., *Atmos. Chem. Phys.* 15(19), 11411-11432, 10.5194/acp-15-11411-2015, 2015.

Jonas M., Bun R., Nahorski Z., et al., *Mitigation and Adaptation Strategies for Global Change.* 24(6), 839-852, 10.1007/s11027-019-09867-4, 2019.

Joos F., Roth R., Fuglestvedt J. S., et al., *Atmos. Chem. Phys.* 13(5), 2793-2825, 10.5194/acp-13-2793-2013, 2013.

Kanaya Y., Yamaji K., Miyakawa T., et al., *Atmos. Chem. Phys. Discuss.* 2019, 1-28, 10.5194/acp-2019-1054, 2019.

Klimont Z., Kupiainen K., Heyes C., et al., *Atmos. Chem. Phys.* 17(14), 8681-8723, 10.5194/acp-17-8681-2017, 2017.

Kupiainen K. J., Aamaas B., Savolahti M., et al., *Atmos. Chem. Phys.* 19(11), 7743-7757, 10.5194/acp-19-7743-2019, 2019.

Lelieveld J., Evans J. S., Fnais M., et al., *Nature.* 525, 367, 10.1038/nature15371, 2015.

Lund M. T., Berntsen T. K. & Fuglestvedt J. S., *Environmental Science & Technology.* 48(24), 14445-14454, 10.1021/es505308g, 2014a.

Lund M. T., Berntsen T. K., Heyes C., et al., *Atmospheric Environment.* 98, 50-58, https://doi.org/10.1016/j.atmosenv.2014.08.033, 2014b.

Lund M. T., Aamaas B., Berntsen T., et al., *Earth Syst. Dynam.* 8(3), 547-563, 10.5194/esd-8-547-2017, 2017.

Lund M. T., Myhre G., Haslerud A. S., et al., *Geosci. Model Dev.* 11(12), 4909-4931, 10.5194/gmd-11-4909-2018, 2018.

Melamed M. L., Schmale J. & von Schneidemesser E., *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., et al., 2013.

O'Neill B. C., Kriegler E., Riahi K., et al., *Climatic Change.* 122(3), 387-400, 10.1007/s10584-013-0905-2, 2014.

Persad G. G. & Caldeira K., *Nature Communications.* 9(1), 3289, 10.1038/s41467-018-05838-6, 2018.

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

Rafaj P., Kiesewetter G., Gül T., et al., *Global Environmental Change.* 53, 1-11, https://doi.org/10.1016/j.gloenvcha.2018.08.008, 2018.

Ramanathan V. & Carmichael G., *Nature Geoscience.* 1(4), 221-227, 10.1038/ngeo156, 2008.

Rao S., Klimont Z., Smith S. J., et al., *Global Environmental Change.* 42, 346-358, https://doi.org/10.1016/j.gloenvcha.2016.05.012, 2017.

Reisinger A. & Clark H., *Global Change Biology.* 24(4), 1749-1761, 10.1111/gcb.13975, 2018.

Riahi K., van Vuuren D. P., Kriegler E., et al., *Global Environmental Change.* 42, 153-168, https://doi.org/10.1016/j.gloenvcha.2016.05.009, 2017.

Ritchie J. & Dowlatabadi H., *Energy.* 140, 1276-1291, https://doi.org/10.1016/j.energy.2017.08.083, 2017.

Rogelj J., Schaeffer M., Meinshausen M., et al., *Proceedings of the National Academy of Sciences.* 111(46), 16325-16330, 10.1073/pnas.1415631111, 2014.

Rogelj J., Meinshausen M., Schaeffer M., et al., *Environmental Research Letters.* 10(7), 075001, 10.1088/1748-9326/10/7/075001, 2015.

Rogelj J., Shindell D., Jiang K., et al., 2018.

Samset B. H. & Myhre G., *Geophysical Research Letters.* 38(24), 10.1029/2011gl049697, 2011.

Samset B. H., Sand M., Smith C. J., et al., *Geophysical Research Letters.* 45(2), 1020-1029, 10.1002/2017gl076079, 2018.

Sand M., Berntsen T. K., von Salzen K., et al., *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., et al., *Science.* 335(6065), 183-189, 10.1126/science.1210026, 2012.

Shindell D. & Smith C. J., *Nature.* 573(7774), 408-411, 10.1038/s41586-019-1554-z, 2019.

Shine K. P., Fuglestvedt J. S., Hailemariam K., et al., *Climatic Change.* 68(3), 281-302, 10.1007/s10584-005-1146-9, 2005.

Shoemaker J. K., Schrag D. P., Molina M. J., et al., *Science.* 342(6164), 1323-1324, 10.1126/science.1240162, 2013.

Skeie R. B., Fuglestvedt J., Berntsen T., et al., *Environmental Research Letters.* 12(2), 024022, 10.1088/1748-9326/aa5b0a, 2017.

Smith C. J., Kramer R. J., Myhre G., et al., *Geophysical Research Letters.* 45(21), 12,023-012,031, 10.1029/2018gl079826, 2018.

Smith P., Nkem J., Calvin K., et al., 2019.

Smith S. J. & Mizrahi A., *Proceedings of the National Academy of Sciences.* 110(35), 14202-14206, 10.1073/pnas.1308470110, 2013.

Steckel J. C., Hilaire J., Jakob M., et al., *Nature Climate Change*, 10.1038/s41558-019-0649-8, 2019.

Stjern C. W., Samset B. H., Myhre G., et al., *Journal of Geophysical Research: Atmospheres.* 122(21), 11,462-411,481, 10.1002/2017JD027326, 2017.

Stohl A., Aamaas B., Amann M., et al., *Atmos. Chem. Phys.* 15(18), 10529-10566, 10.5194/acp-15-10529-2015, 2015.

Søvde O. A., Prather M. J., Isaksen I. S. A., et al., *Geosci. Model Dev.* 5(6), 1441-1469, 10.5194/gmd-5-1441-2012, 2012.

Takemura T. & Suzuki K., *Scientific Reports.* 9(1), 4419, 10.1038/s41598-019-41181-6, 2019.

Tokarska K. B., Stolpe M. B., Sippel S., et al., *Science Advances.* 6(12), eaaz9549, 10.1126/sciadv.aaz9549, 2020.

UNEP, 2011.

UNEP, 2017.

UNEP, 2018.

UNEP, 2019.

Unger N., Bond T. C., Wang J. S., et al., *Proceedings of the National Academy of Sciences.* 107(8), 3382-3387, 10.1073/pnas.0906548107, 2010.

Wilcox L. J., Liu Z., Samset B. H., et al., *Atmos. Chem. Phys. Discuss.* 2020, 1-30, 10.5194/acp-2019-1188, 2020.

Xu Y. & Ramanathan V., *Proceedings of the National Academy of Sciences.* 114(39), 10315-10323, 10.1073/pnas.1618481114, 2017.

Zelinka M. D., Myers T. A., McCoy D. T., et al., *Geophysical Research Letters.* 47(1), e2019GL085782, 10.1029/2019gl085782, 2020.

Zheng B., Tong D., Li M., et al., *Atmos. Chem. Phys.* 18(19), 14095-14111, 10.5194/acp-18-14095-2018, 2018.

Aamaas B., Peters G. P. & Fuglestvedt J. S., *Earth Syst. Dynam.* 4(1), 145-170, 10.5194/esd-4-145-2013, 2013.

Aamaas B., Berntsen T. K. & Samset B. H., *Atmos. Chem. Phys.* 19(24), 15235-15245, 10.5194/acp-19-15235-2019, 2019.

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 species considered in the idealized emission reduction packages, ~~policies and~~ the percentage reduction assumed and example policies~~species reduced~~. All percentages refer the total emissions of a given sector, not total anthropogenic.

Sector	Package 1 (P1)	Package 2 (P2)	Package 3 (P3)
ENE [a)]	End-of-pipe measures	Reduced loss in fossil fuel production and distribution	Climate strategy
	SO_2 (85%) NOx (75%)	CH_4 (75%), BC (85%) CO_2 (3%)[b)]	CO_2 (65%), CH_4 (40%) SO_2 (65%), NOx (45%) BC (35%)
AGR	Nitrogen use efficiency and technical improvements	Meat reduction	Increase in biogas use
	NH_3 (65%) NOx (60%)	CH_4 (35%) NH_3 (75%) NOx (75%)	CH_4 (2%) NH_3 (10%) CO_2 (negligible)
SHP	Scrubbers and particulate filters	Slow-steaming [d)]	Strong increase in LNG capacity
	SO_2 (95%) [c)] NOx (75%) BC (85%)	CO_2 (35%) SO_2, NO_x, (35%) BC (20%)	CO_2 (5%) SO_2, (90%) NO_x, (55%) BC (30%)

a) Here stationary combustion in power and industry.
b) Through use of recovered CH4 instead of coal as fuel in oil, gas and coal industry.
c) The reduction level is based on a year 2015 baseline with relatively high sulfur content for international shipping
d) Assuming about 20% reduction in speed

Figures:

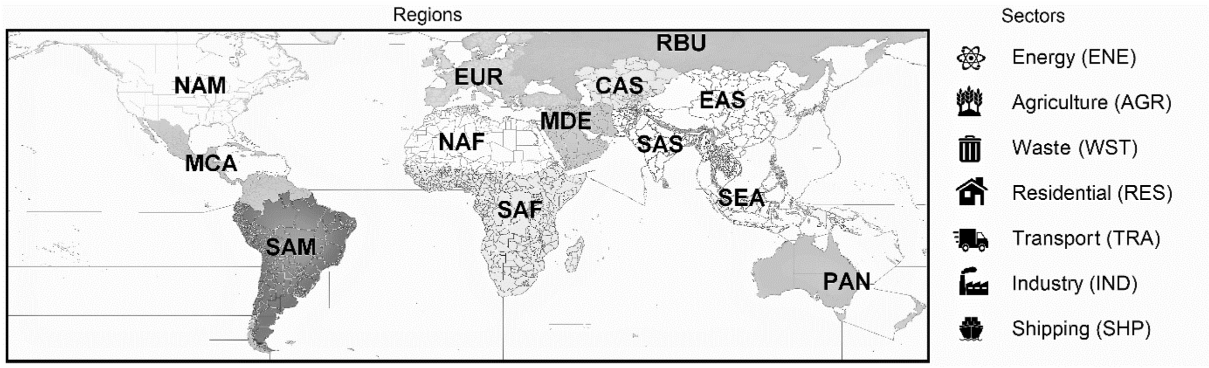
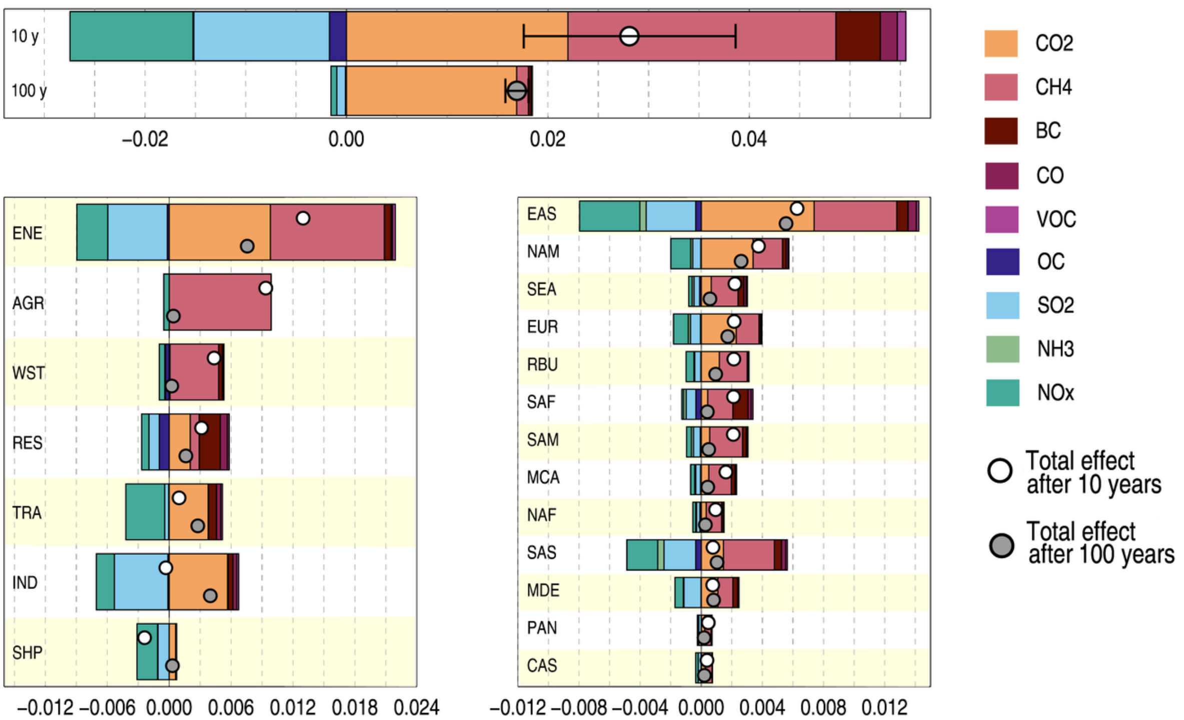


Figure 1: Emission source regions and sectors used in the analysis.



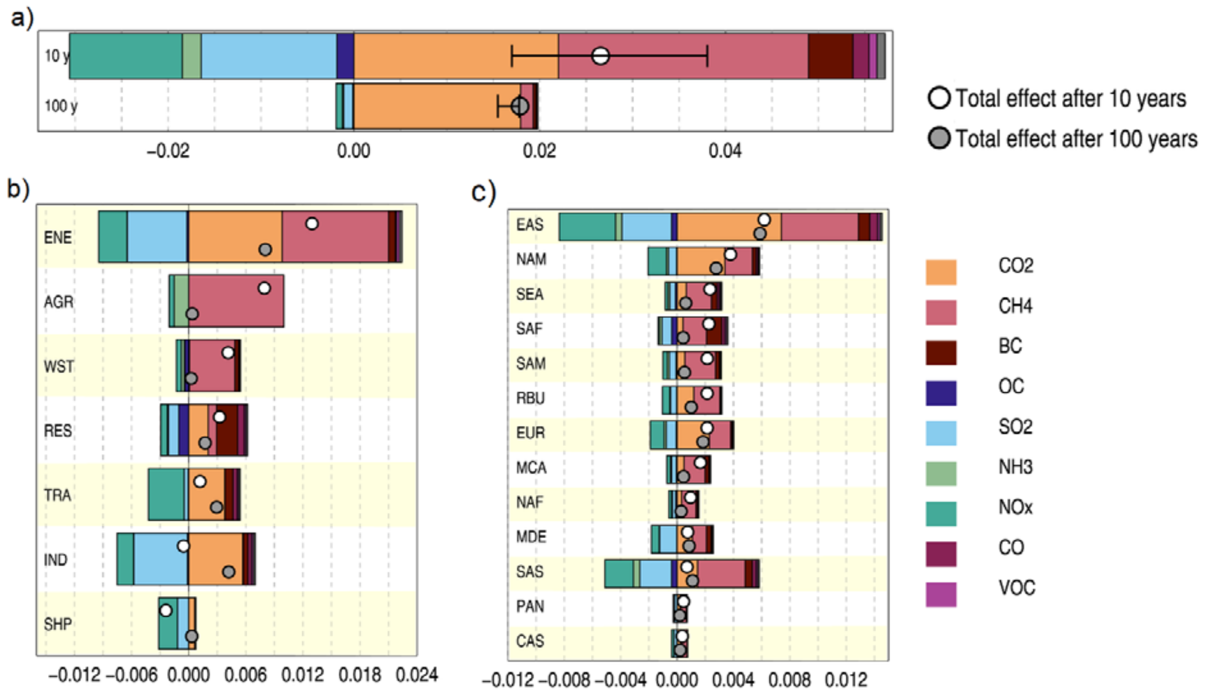
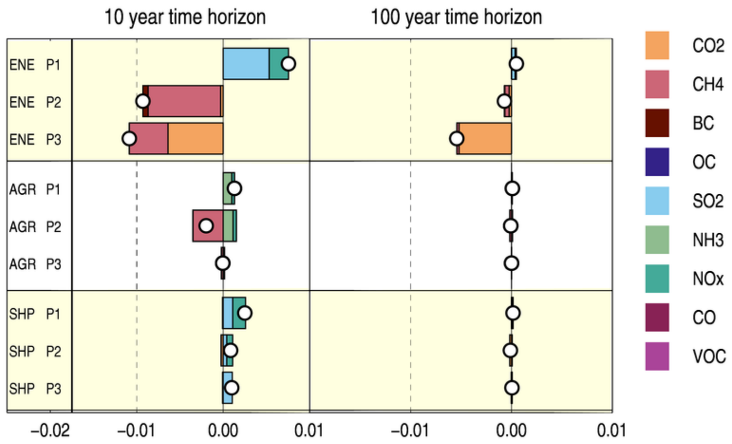


Figure 2: Global-mean surface temperature impact 10 and 100 years after one year of present-day (i.e., year 2014) emissions of SLCFs and CO_2 for: a) global total emissions, b) emissions from seven major economic sectors, and c) total (i.e., sum of all sectors) emissions in 13 sources regions. Panels 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.



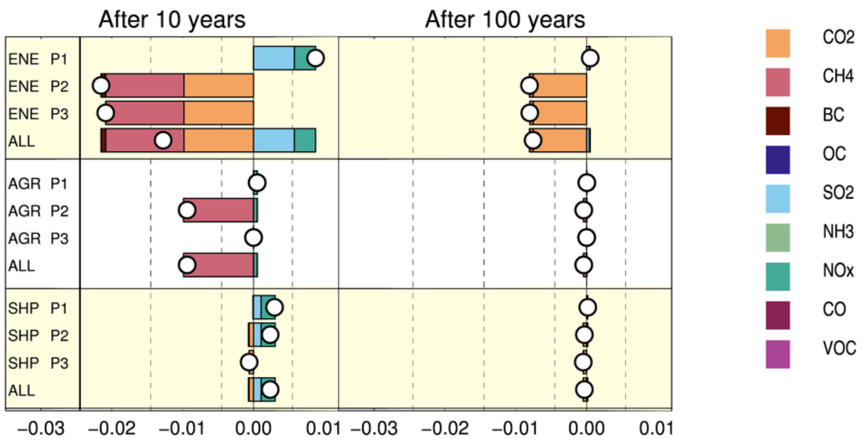


Figure 3: Global-mean surface temperature impact on ~~after~~ 10 and 100 year~~s~~ time horizons resulting from instantaneous reductions of different sets (listed in Table 2) of SLCFs and CO_2 emissions ~~under three different policies, as well as for these three combined~~. White circles indicate the net impact of these reductions.

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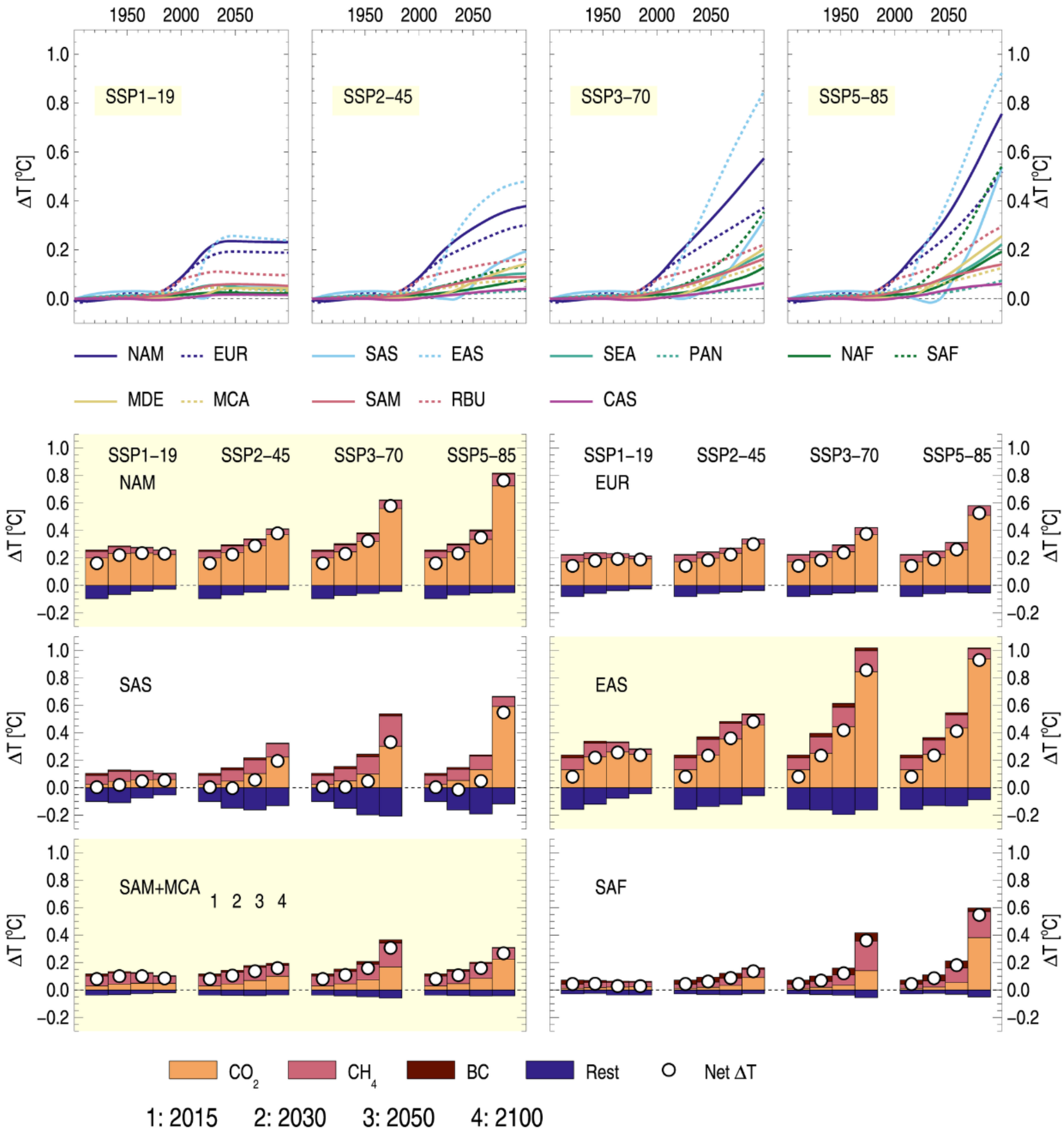


1950 2000 2050
SSP1–19
SSP2–45
SSP3–70
SSP5–85
ΔT [°C]
NAM EUR SAS EAS SEA PAN NAF SAF
MDE MCA SAM RBU CAS
NAM
EUR
SAS
EAS
SAM+MCA
1 2 3 4
SAF
CO2 CH4 BC Rest Net ΔT
1: 2015 2: 2030 3: 2050 4: 2100

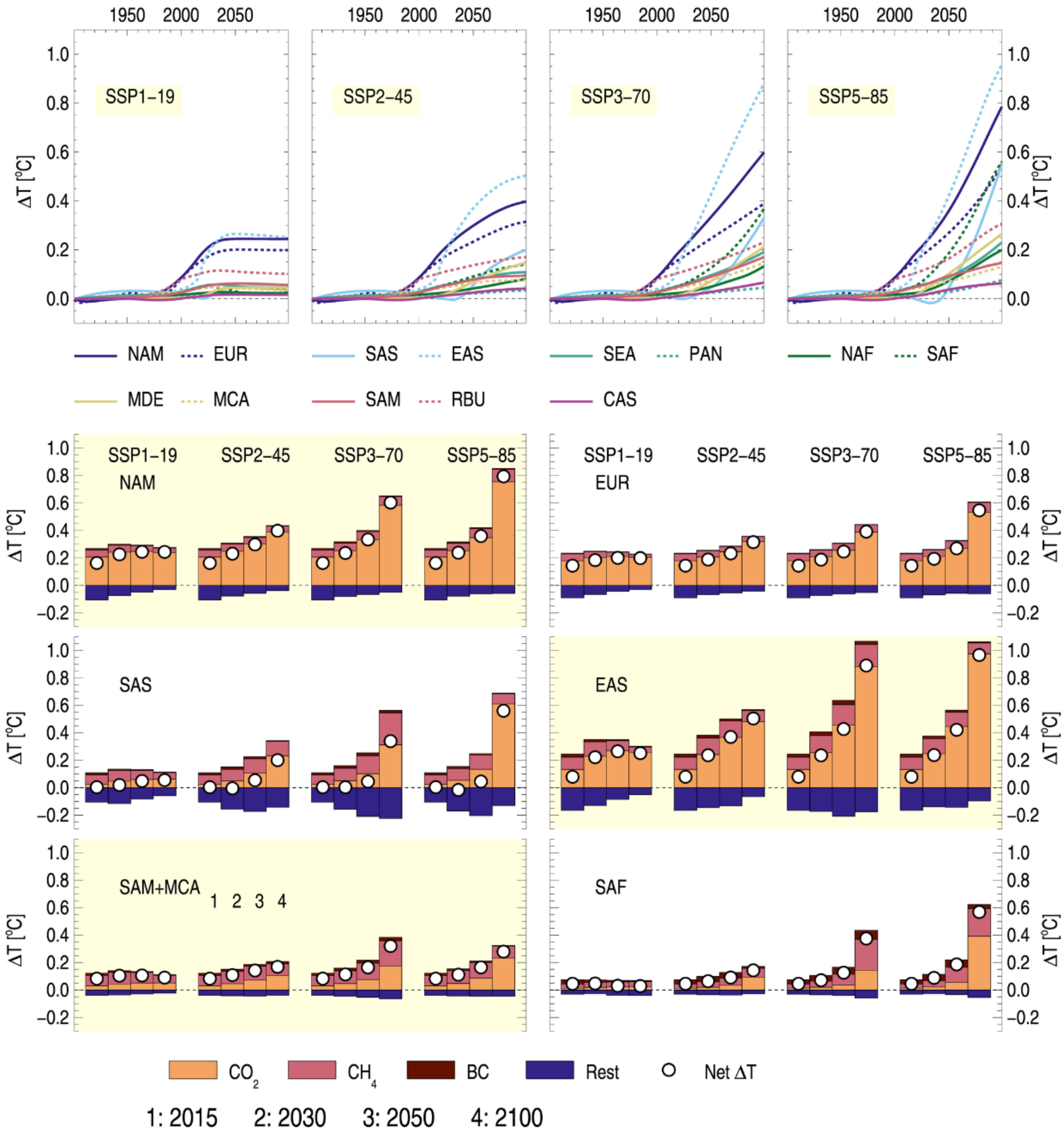
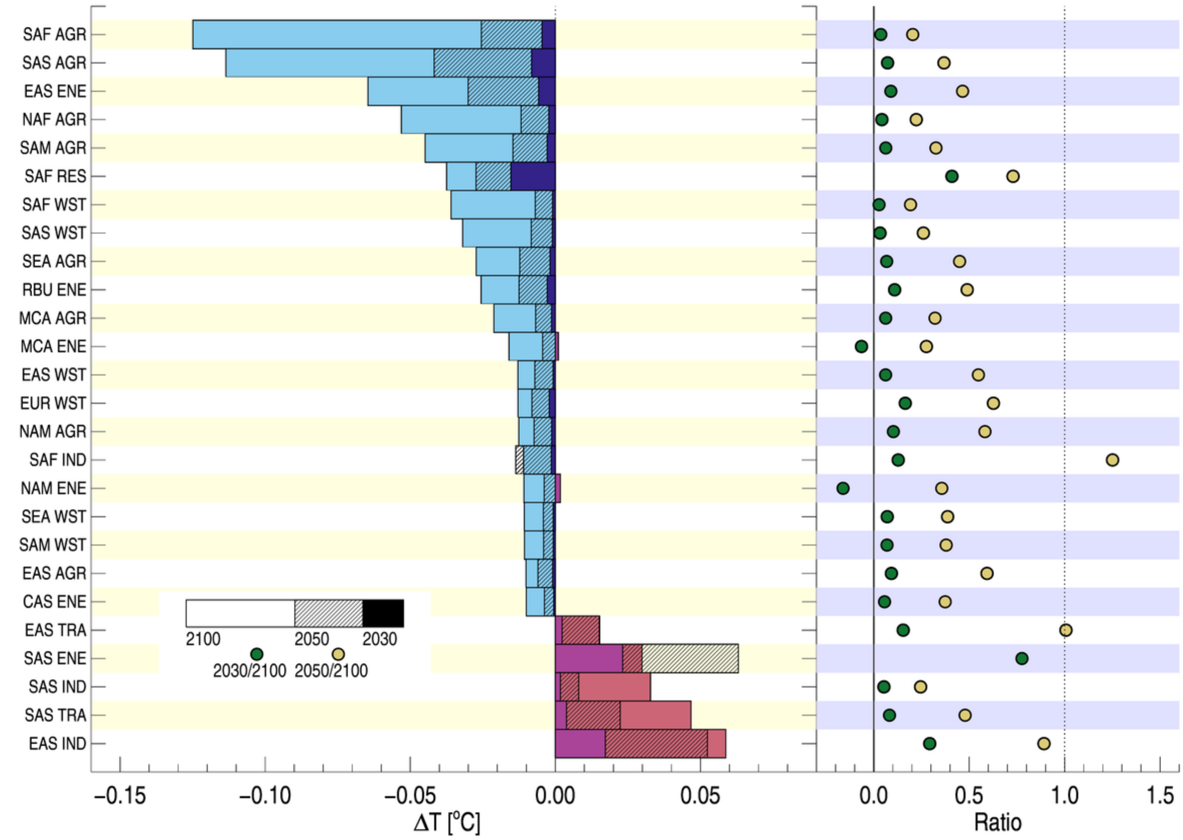


Figure 4: Global mean temperature response to historical emissions and future SSP pathways: a) Net (i.e., sum over all species and sectors) response over the period 1900 to 2100 for each region and scenario and b) net response in 2015, 2030, 2050 and 2100 to emissions in six regions broken down by contributions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



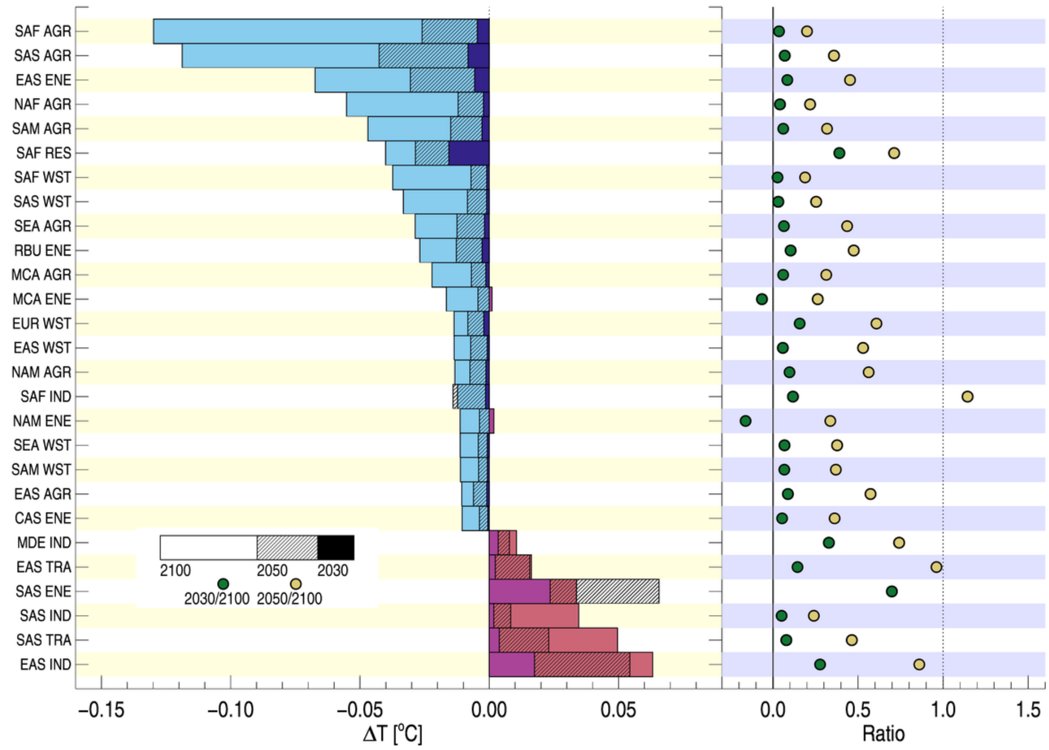


Figure 5: Difference in net SLCF (i.e., sum of all components except CO_2) temperature response between SSP1-1.9 and SSP3-7.0 in 2030, 2050 and 2100 by region and sector. Only combinations of sectors and regions where the differences in global temperature response is larger than ±0.01 °C are shown. For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

Section S1 Sensitivity of our results to IRF choices

The AGTP depends on the choice of CO_2 and climate response impulse response function (IRF). To explore this sensitivity in more detail, we repeat our calculations using alternative climate and CO_2 IRF combinations. Figure S1 show the AGTPs as a function of time for CO_2, CH_4 and SO_2. The largest difference is seen between results using the B&R08 climate IRF (Boucher & Reddy, 2008) and the G13 (Geoffroy et al., 2013) and G17 (Gasser et al., 2017) IRFs (all with the Joos et al. (2013) CO_2 IRF). The longer time scales of the climate system response in B&R08 compared to both G13 and G17, results in an AGTP that is lower up to approx. 15 years and higher after for CH4 and CO2, and stronger (i.e., more negative) for SO_2 already after 5 years. Although we do not present relative metrics here, we note that they would differ from values reported by the Fifth Assessment Report by the IPCC (AR5), who used the B&R08 IRF (Myhre et al., 2013). As an illustration, Table S1 shows the GTP for methane for time horizons 10, 20 and 100 years (a detailed comparison for the other SLCFs is difficult due to different underlying radiative efficiencies). We also show values taken from the IPCC AR5. The difference between AR5 and values calculated using the B&R08 IRF in the present study arises from the 14% increase in the radiative efficiency of methane that we apply based on (Etminan et al., 2016). Using G13 or G17 climate IRFs result in 4-18% lower GTPs compared to those based on B&R08 for two short time horizons, and increased metric values in 100-year horizon. Using the CO2 IRF without the carbon-climate feedback included from Gasser et al. (2017) increases the methane GTP by 2, 5 and 11% for 10, 20 and 100 years, respectively, compared to using the corresponding IRF with carbon climate feedback. As noted by Gasser et al. (2017) this difference can be larger for shorter-lived species like BC and SO_2.

We also investigate what the choice of IRFs mean for our global and regional near- and long-term temperature responses. Figure S2 shows the global-mean surface temperature response following global present-day emissions using results with the B&R08, G13 and G17 climate response IRFs. The two latter yields similar results, while the total effect after 10 years is lower with B&R08 due to a combination of smaller contributions from CH_4 and CO_2 and stronger cooling contributions. We also note that while the overall picture of regional and sectoral SLCF and CO_2 contributions remains the same, these differences between B&R08 and G13 are sufficient to affect the ranking by total net near-term temperature impact of some regions and sectors compared to our main Fig.2. For instance, stronger cooling contributions reduces the net warming of the ENE sectors, moving AGR up as the sectors with the largest net temperature impact. Similarly, SAS and MDE, regions with significant cooling emissions and relatively small CO2 emissions, are moved down. The net temperature response to emissions in SAS switches from to a small net negative on the 10-year timescale.

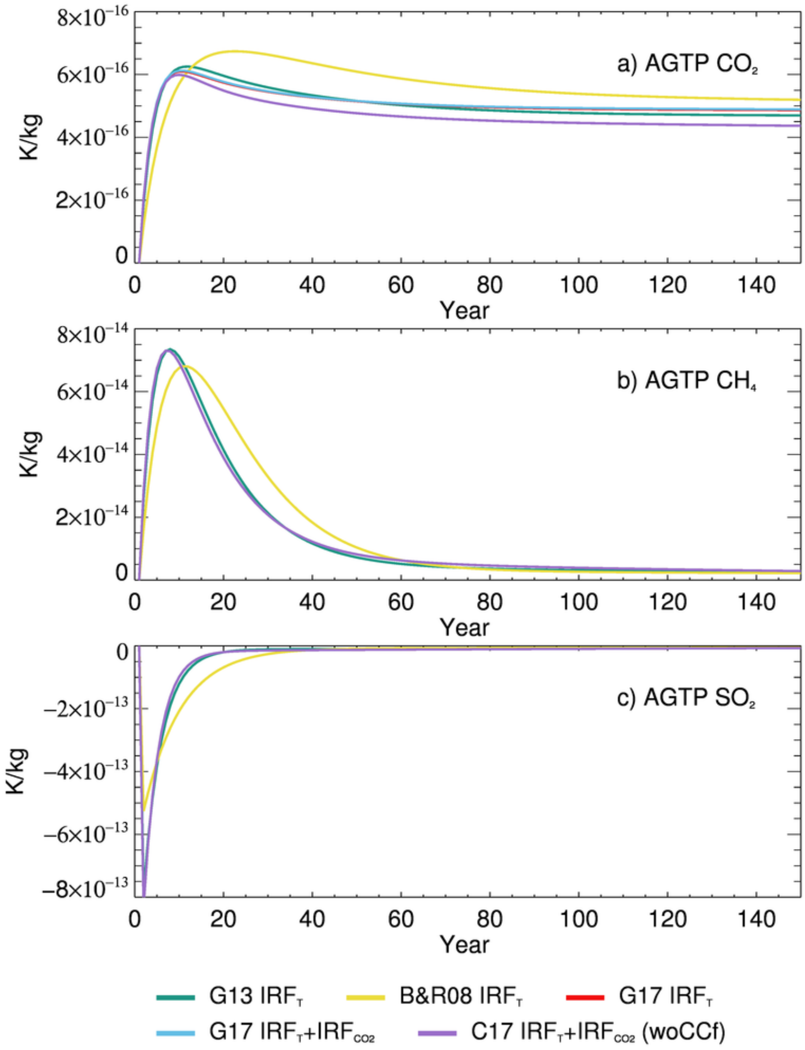


Figure S1: AGTP(t) for CO_2, CH_4 and SO_2 as calculated using different combinations of climate response and carbon dioxide impulse response functions: B&R08 (Boucher & Reddy, 2008), G13 (Geoffroy et al., 2013) and G17 (Gasser et al., 2017) (all with the Joos et al. (2013) CO_2 IRF), and G17 with corresponding CO_2 IRFs with and without the carbon-climate feedback included.

Table S1: GTPs for methane using different combinations of climate response and CO_2 IRFs.

	GTP of methane		
Time horizon	10	20	100
AR5	100	64	4
B&R08 IRF_T	114	77	5
G13 IRF_T	109	65	6
G17 IRF_T	108	63	8
G17 IRF_T+IRF_{CO2}	108	63	8
G17 IRF_T+IRF_{CO2} (noCCf)	110	67	9

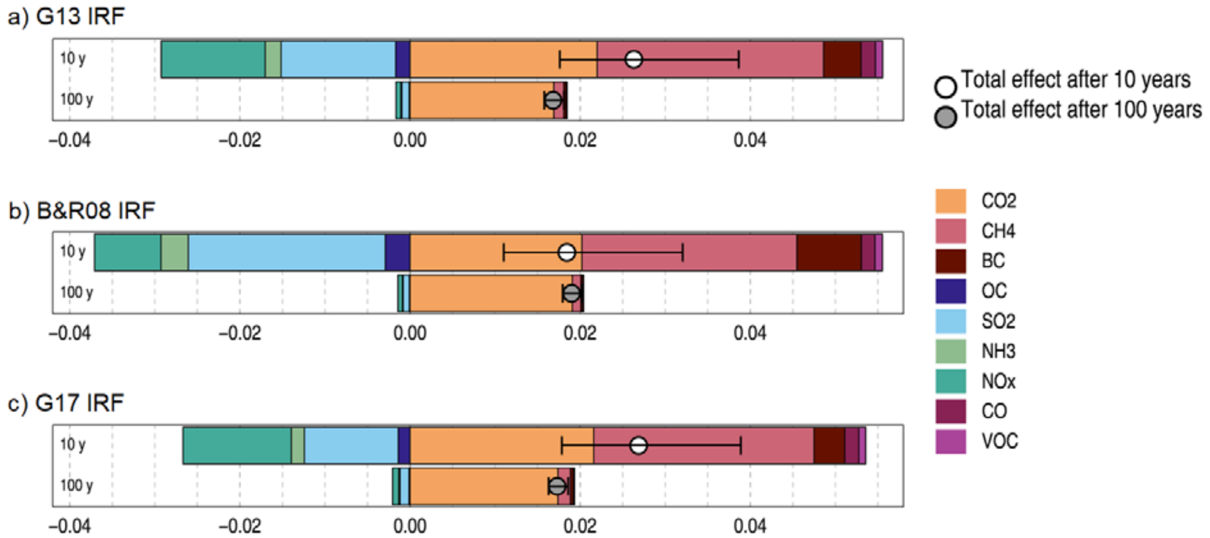
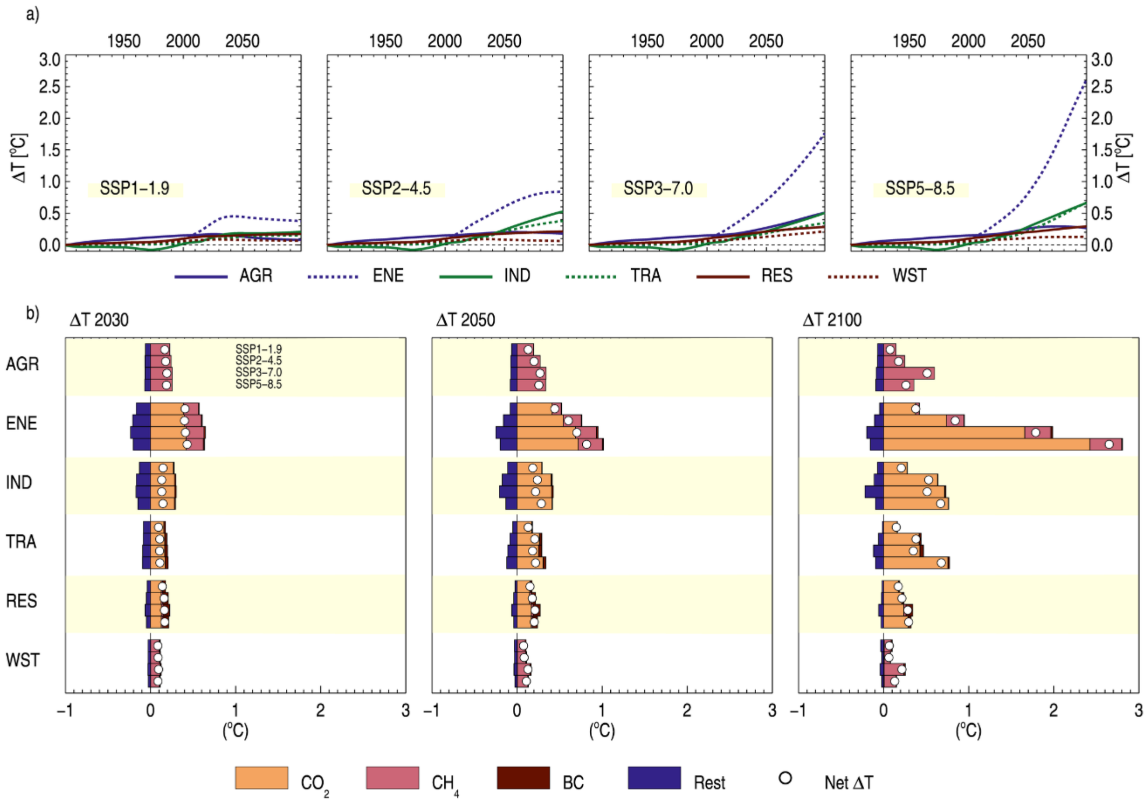


Figure S2: Global-mean surface temperature impact 10 and 100 years after one year of global present-day (i.e., year 2014) emissions of SLCFs and CO_2, calculated using different combinations of climate response and CO_2 IRFs.



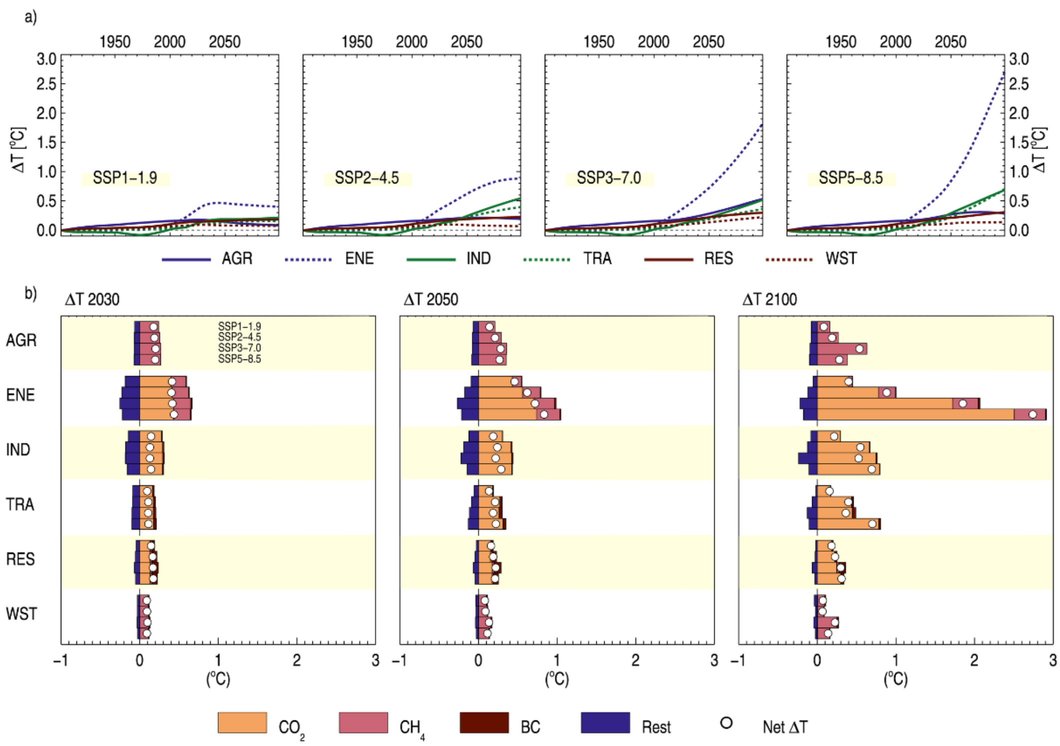
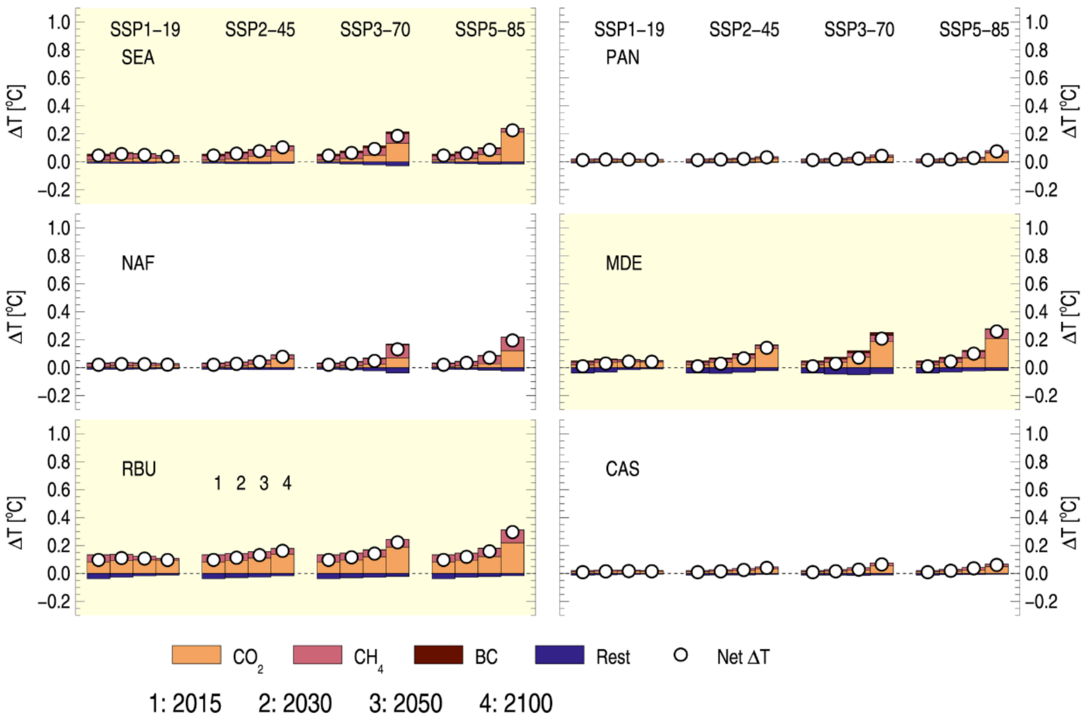


Figure S3~~1~~: Global mean temperature response to historical emissions and future SSP pathways: a) Net (i.e., sum over all species and regions) response over the period 1900 to 2100 for each sector and scenario and b) net response in 2030, 2050 and 2100 to emissions in six of *our seven sectors (excluding shipping, which remains much smaller than the rest), broken down by contributions from CO_2, BC, methane and the sum of SO_2, OC, NH_3 and ozone precursors ("Rest").*



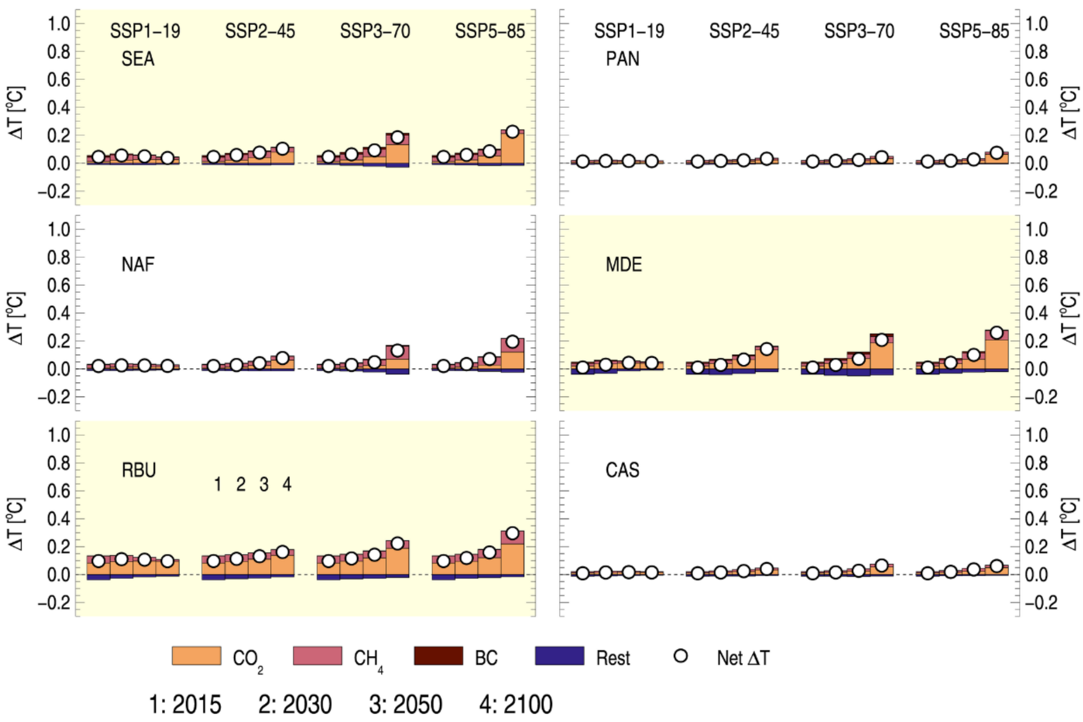


Figure S4~~2~~: Global mean temperature response to historical emissions and future SSP pathways: Net response in 2015, 2030, 2050 and 2100 to emissions in six regions broken down *by contributions from CO_2, BC, methane and the sum of SO_2, OC, NH_3 and ozone precursors (i.e., "Rest").*

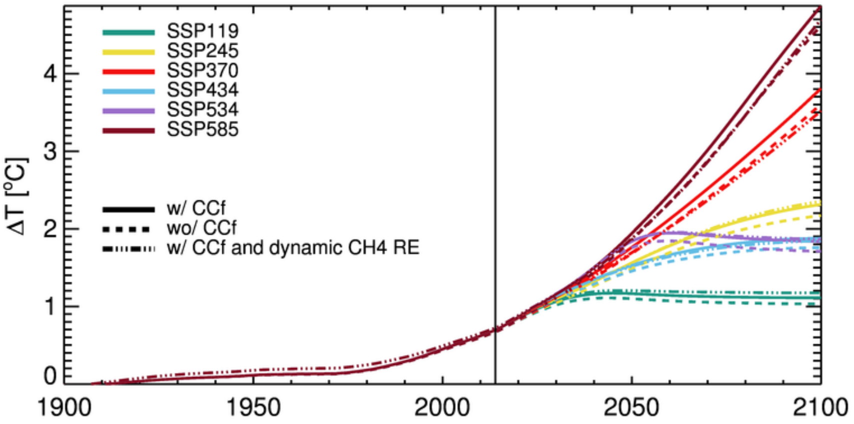


Figure S5: Impact of including carbon-climate feedback and dynamical methane radiative efficiency in the AGTP calculation on global mean total net temperature response to total emissions (i.e. sum of our sectors and regions) under 6 of the SSP-RCPs.

References:

Boucher O. & Reddy M. S., *Energy Policy.* 36(1), 193-200, https://doi.org/10.1016/j.enpol.2007.08.039, 2008.

Etminan M., Myhre G., Highwood E. J., et al., *Geophysical Research Letters.* 43(24), 12,614-612,623, 10.1002/2016gl071930, 2016.

Gasser T., Peters G. P., Fuglestvedt J. S., et al., *Earth Syst. Dynam.* 8(2), 235-253, 10.5194/esd-8-235-2017, 2017.

Geoffroy O., Saint-Martin D., Olivié D. J. L., et al., *Journal of Climate.* 26(6), 1841-1857, 10.1175/jcli-d-12-00195.1, 2013.

Joos F., Roth R., Fuglestvedt J. S., et al., *Atmos. Chem. Phys.* 13(5), 2793-2825, 10.5194/acp-13-2793-2013, 2013.

Myhre G., Shindell D., Brèon F.-M., et al., 2013.