Response to review of "*Emission metrics for quantifying regional climate impacts of aviation*" by Marianne T. Lund, Borgar Aamaas, Terje Berntsen, Lisa Bock, Ulrike Burkhardt, Jan S. Fuglestvedt and Keith P. Shine

We thank the reviewer for the careful review and useful comments and suggestions. Responses to individual comments are given below.

Anonymous Referee #1

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This manuscript attempts to calculate Global Warming Potentials (GWP), Global Temperature Potentials (GTP) and Absolute Regional Temperature change Potential (ARTP) for aviation emissions. This is a difficult paper to put together since there is essentially I think an important negative conclusion that this method does not work that well for aviation emissions. I would like to see a bit more uncertainty analysis to quantify where the problems are. I think a bit more discussion of the physics of the climate system would help the reader understand the problems with this method. This paper could be publishable with some important revisions.

Generally, it looks like the method described is highly model dependent, which is not really obvious until the end of the paper, and there is not really quantification of the uncertainty. I think this could be better woven throughout. It would be nice to comment a bit more on how Stohl et al 2015 and Shindell 2012 apply to these results: I am pretty convinced that for small perturbations and for non-gaseous species like contrails that these results may not apply.

I think that this work could also use a better focus on some of the physical aspects of the climate system and the feedbacks that might or might not operate. And at a minimum I would like to see quantification of uncertainty in the different parts of the ARTP terms.

Some of the figures (e.g. Fig 3 and S1) could use some clarification as noted below.

The general points are addressed through responses to the following specific comments, where the issues are raised again.

Specific comments are below.

Page 4, L108: how does any of this work account for effects on the coupled climate system? Regional forcing can show up very differently in surface temperature depending on whether the energy goes into sensible heat, latent heat, or evaporation, and will depend on surface type and coupled modes of the climate system. For example: cooling the N. Atlantic deep water formation region with contrails may simply cool deep water and not be felt at the surface. Or it may alter the formation of deep water itself. Don't you need a coupled climate model to do this?

The ARTPs are indeed calculated using input from a coupled climate model. The basis for the ARTP is the regional climate sensitivities for four latitude bands, i.e., relationships between the pattern of RF caused by a certain forcing mechanism and the consequent surface temperature in a given latitude region. These relationships are established from simulations with the GISS climate model and hence incorporate the response of the coupled climate system to the different forcing mechanisms and regions.

To fully account for the detailed regional temperature responses, one would naturally need a coupled climate model, for instance to capture potential changes in regional responses in a climate differing considerably from the present state. Currently, assessing the impact of individual sectors or mitigation measures is challenging and costly given the large natural variability of the global climate models, and requires significant resources and high technical skill. Emission metrics cannot replace the detailed information from climate models, but they serve as very useful tools to provide first-order estimates of the climate impact of various emissions, and they are based on information from complex models. Until recently, emission metrics have used globally averaged input to produced globally average impacts. Being able to include spatial information is an important step, in particular for the short-lived climate forcers that produce more heterogeneous RF than CO_2.

Although we believe we stated clearly the coupled-climate model origin of our ARTP values, at lines 198-200, to further emphasize this point, we have added the following in the introduction: *"The ARTP uses a set of regional climate sensitivities to provide time-varying surface temperature response in four latitude bands to emissions, accounting for the regional RF caused by the emissions. These sensitivities are derived from simulations with a coupled climate model and express the relationship between the pattern of a radiative forcing and the consequent surface temperature in a given latitude band."*

Page 4, L110: I'm not sure you can do this with a CTM. The circulation doesn't adjust.
We realize that this sentence is unclear. As the reviewer points out, the emission metrics cannot be calculated directly from the combination of CTM simulations and radiative transfer modeling, but must include a representation of the climate (temperature) response to the given forcing. The CTM plus radiative transfer calculations allows us to capture detailed atmospheric chemistry and forcing. For emission metrics, the climate response is represented by an impulse response function. This is a simplified, global mean function, but is based on more complex climate models. In our analysis, we also use regional climate sensitivities which are based on coupled climate model simulations in order to capture information about the spatial distribution of the temperature response depending on the forcing mechanism and location.

To clarify, we have rephrased:
"In this study we calculate GWP, GTP and ARTP for global and regional aviation emissions. We consider a broad set of forcing mechanisms and emissions in six separate source regions. Input of the aviation-induced radiative forcing of ozone and aerosols are obtained from simulations with the chemistry-transport model OsloCTM3 (Søvde et al., 2012) and radiative transfer calculations, while the radiative forcing from the formation contrail-cirrus is simulated with the ECHAM5-CCMod (Bock & Burkhardt, 2016b; a). Calculating global and regional emission metrics allows us to capture (…)"

Page 5, L114: again: surface temperature response depends on the surface type. Is that accounted for?

The regional climate sensitivities that form the basis for the ARTP calculations are derived from simulations with a couple climate model, which includes a dependence on the surface type. See also response to the comment above.

Page 5, L117: how uncertain are the regional climate sensitivities?
This is a very good question. A full set of regional climate sensitivities (RCS) have so far only been estimated using one climate model by Shindell and Faluvegi (2009). Standard deviations over the 80 year model integrations show quite some variability in the response to certain species, at least in some regions. Two studies have repeated the experiments from Shindell and Faluvegi (2009) for BC with similar findings in terms of spatial distribution of forcing-response (Sand et al. 2013; Flanner 2013). The coefficients also seem fairly robust compared to the response to historical aerosol forcing in several other climate models (Shindell 2012). However, a formal quantification of their uncertainty is currently not possible and repeating the experiments to establish sensitivities with additional climate models is beyond the scope of this study, and would likely require a dedicated intercomparison exercise. Baker et al. (2015) showed that the zonal mean temperature response to BC emissions can differ significantly between different climate models both in magnitude and spatial distribution, while the models agreed better for SO_2 emissions. Some degree of model dependence in the RCSs cannot be excluded, in particular for some species.

To make the potential model dependence clear earlier in the manuscript, we have specified in the final paragraph of the introduction that the sensitivities have so far only been derived by one climate model. We have also incorporated some of the information above in the text.

Page 7, L173: I do not think you can throw out this term: it is a compensating effect or feedback. You could include the reduction in cirrus as a separate forcing, but now you are overstating the contrail impact.
We agree with the reviewer here and have included the 20% reduction in the RF of contrail-cirrus, assuming it is spatially constant, i.e., that the same impact occurs in each of our emission source regions.

Page 7, L184: What are these uncertainties?
We have clarified this sentence and added references to studies showing how there is a large range in aviation RF estimates reported in the existing literature. The sentence also fits better after the first two sentences in this paragraph and has been moved up. It now reads:
"It should be noted that there is a broad range in the estimates of RF caused by the various aviation emissions reported in the literature (e.g., Brasseur et al. (2016); Lee et al. (2009)) and such uncertainties in RF will propagate to the emissions metrics."

Page 7, L197: Does previous work show that this represents the physical response?
I have a hard time believing it works for non-uniform emissions in the vertical, or for aviation emissions.
The regional climate sensitivities are based on coupled simulations with the GISS model. One can argue whether current climate models represent the physical response, but they are at present the only tools we have.

As described later in the manuscript, the GISS simulations involve perturbing the RF resulting from anthropogenic emissions from all sources. Since, as the reviewer points out, the temperature response per unit RF can depend on the altitude of the RF for some species and regions, applying the sensitivities to situations which differ significantly from that originally used to derive them does introduce uncertainties. This is precisely why we take the analysis one step further to evaluate the application and point to where more research is needed in order to improve the general applicability of the ARTP.

Page 7, L200: Are these done for contrails? This is a cloud forcing, which is very different than other forcings. For example: contrail forcing is a SW and LW forcing that depends strongly on surface albedo. Do these sensitivities take account of that? If not, I'm not sure the method is valid.
We feel that the text starting at line 221 made clear what RTPs are used for the contrail-cirrus case, and the limitations of the assumptions we made.

The contrail-cirrus RF is quantified through detailed simulations with the ECHAM5-CCMod and takes the surface type and other cloudiness into account.

In terms of temperature response, we do not have regional sensitivities that have been derived from climate model simulations specifically for contrails (as we noted at line 221 to 223). Currently, such information does not exist in the literature, and we recognize that this introduces additional uncertainties in our analysis. To represent the regional response to a regional contrail-cirrus RF, we use the sensitivities based on the forcing-response relationship for CO_2 and sulfate. This includes trapping of long-wave radiation and reflection in the short-wave and the sulfate forcing likewise, as is well established, depends strongly on surface albedo. As described above, the sensitivities are based on coupled climate model simulations, which includes the dependence on surface type – for the CO_2 and sulfate forcing.

As we noted at line 226, the only two available studies of the climate response to contrails have shown that the global efficacy of line shaped contrails could be significantly lower than one, and the reasons for this may well be as a result of the distinct nature of the contrail forcing which the reviewer mentions. This lower surface temperature response per unit forcing compared to CO_2 could be accounted in our (and future) calculations by scaling the temperature response (as we discuss in Sect. 3.3). However, we do not have any information about how the efficacy could vary regionally, as we noted at line 229.

Page 8, L202: What does the statement in parentheses mean? What is a component? If the time is longer than the lifetime for a pulse emission, isn't the forcing gone?
This statement has been corrected, clarified and moved to the beginning of the next paragraph: *"Equation 4 can be used for short-lived species where H is significantly longer than the lifetime of the species (typically days to weeks)."*

Page 8, L207: This presumes that all RF is created equal with respect to sensitivity. I think this is valid for GHG in the IR. I'm not sure if it is valid for SW effects, and probably not for clouds.

This is an important point. We already touch upon this issue in the following paragraph on efficacy, but we agree that a more detailed discussion would be valuable. Efficacies can be included in the application of metrics by adding a scaling factor, and will act to reduce or increase the temperature change to emissions. However, only a couple of studies have investigated the (global-mean) efficacy for aviation-induced forcing mechanisms and are limited to line shaped contrails and ozone, and we therefore include efficacy only as a point for discussion in Sect. 3.3.

The concept of efficacy, or climate sensitivity parameters, also relates to the RCS (as the reviewer touches upon in the next comment). These are in themselves a type of climate sensitivity parameters for the four forcing agents considered in the Shindell and Faluvegi (2009) study (BC, ozone, sulfate and CO_2), expressing differences arising from the forcing distribution in the horizontal.

We have therefore the discussion and added:
"The temperature response per unit RF can differ between different forcing mechanisms, i.e., mechanisms can have their specific climate sensitivity parameter. This is often expressed as efficacy, defined as the ratio of the climate sensitivity parameter for a given forcing agent to that for specified changes in CO2 (Hansen et al., 2005). Efficacies can be included in the metric application as a scaling factor. However, presently only a few studies have investigated the efficacy of selected aviation-induced forcing mechanisms. The efficacy depends primarily on the spatial distribution of the RF, both in the horizontal and vertical. The $RCS_{i,l,m}$ *implicitly include differences in efficacy of individual components arising from the horizontal forcing distribution (to the extent that the driving processes are accounted for the underlying climate model simulations). The* $RCS_{i,l,m}$ *are established for the four forcing agents BC, ozone, sulfate and CO2. Contrail-specific regional sensitivities do so far not exist. By using the average sensitivities of sulfate and CO2 to calculate the contrail ARTPs, we include both a longwave absorption and a shortwave scattering component. The efficacy of scattering aerosols and greenhouse gases is also likely less dependent on altitude than for absorbing aerosols. However, studies have indicated that the contrail efficacy may be as low as 0.3-0.6 (Ponater et al., 2005; Rap et al., 2010). Furthermore, little or no information about the dependence of the climate sensitivity parameter of contrails on the horizontal forcing distribution exist. It should also be noted that efficacies from the small sector-specific forcings can currently only be derived by scaling them to produce a forcing large enough to get a significant response in the model. This add an additional uncertainty to deriving reliable* $RCS_{i,l,m}$*. Using the* $RCS_{i,l,m}$ *for a different forcing agent to approximate the response to contrail-cirrus allows us to include a broader set of aviation-induced forcing mechanisms in our analysis, but is also an important caveat. As discussed in more detail in Sect. 3.4, the climate sensitivity parameter can also depend on altitude, in particular for absorbing aerosols and ozone in certain regions. We explore potential uncertainties in our analysis arising from such vertical differences by comparing the temperature responses estimated using the* $RCS_{i,l,m}$ *with temperature simulated by three additional climate models (see Sect. 2.3)."*

Page 9, L229: So you are trying to put these uncertainties into ’efficacy’, which would affect the contrails by a factor of 2, but then ignore it? I don’t think that is appropriate. Efficacy might be a way to address some of the issues I am referring to with contrails in this context.
The issue of efficacy is not ignored, but brought up again in Sect. 3.3, where we discuss how a lower contrail efficacy may affect the regional temperature response to present-day aviation emissions estimated with the ARTPs. However, currently, only two studies have estimated the efficacy of contrails and estimates of efficacy of other aviation-induced forcing mechanisms are very scarce (one study looked at aviation ozone). We emphasize again that these two studies provide information on the global-mean efficacy but we have no information about how this would influence regional climate sensitivities. Furthermore, in response to the question above, we have added a more detailed discussion about efficacy in general.

Page 9, L241: There are emissions scenarios for aviation that specifically address the non-uniform growth of emissions and the efficiency improvements. Why not use them? There are already RF estimates in the literature with these scenarios.
Here we try to relate RF to an emission and discuss whether to relate contrail RF to flown distance or to fuel use. Since fuel efficiency changes with time, the two metrics would give different results. Simulations for future air traffic do not help with the decision how to formulate the metric.

An assessment of the contrail formation and RF from regional aviation emissions under a different emission scenario and climate would of course be an interesting study on its own. However, repeating the regional model runs with a different emission inventory requires resources beyond what we have available. Our global emission metric calculations could be repeated using input of RF from studies that the reviewer alludes to and could make an interesting sensitivity study. However, since we focus primarily on the regional metrics here, we leave this to further applications of our framework.

Page 10, L270: I do not think the climate system is linear enough to small perturbations to make this a valid assumption. Can you provide a reference demonstrating that multiplying a forcing by an order of magnitude or more yields a linear scaling to the response to the small perturbation in a coupled climate model? I see now there is a reference below. Is it valid?
Here, the reviewer seems to questions the approach and requests a citation, but then (without any justification) questions the validity of our citation upon discovering that we already have one.

Applying a scaling factor (or performing very long model integrations) is a common approach that makes it possible to use climate models to study the response to specific sectors or perturbations. Because of their small size, the use of unscaled forcings to derive reliable responses is very challenging and costly due to the climate model’s internal variability.

The Shine et al. (2012) study illustrates that non-linearities may indeed arise from using different scaling factors in the specific case of BC perturbations from road transport. In contrast, the experiments carried out by Mahajan et al. (2013) (BC x 1, 2, 5 and 10 in the CAM4) actually show a quite linear relationship between the magnitude of the BC perturbation and global temperature response. Nonetheless, this is why we encourage the reader to keep the potential uncertainties in mind when interpreting the absolute magnitudes of the simulated temperature response (see response to next comment).

Page 10, L274: But isn't the temperature response the heart of this paper? Yet it is to be used 'with care'? I think you might need to quantify the potential uncertainties here.
At the core of the evaluation of our metrics against the additional climate model simulations is the geographical pattern of temperature response. The sentence in question aims to caution the reader against potential uncertainties in *absolute magnitude* that may arise from applying a scaling factor in the climate model (as the reviewer also points out in the comment above). A quantification of uncertainties arising from the use of different magnitude scaling factors require a large set of additional model simulations and is beyond the scope of the study. However, we agree that this can be made clearer and have rephrased:

"(…) and potential uncertainties should be kept in mind when considering the absolute magnitude of temperature responses."

Page 10, L278: I do not think figure S1 is correct. I do not see how a 2ppb ozone perturbation causes a 1K surface temperature change in Figure S1. Please clarify or justify that.
Fig. S1A shows the ozone perturbation caused by present-day aviation NOx emissions simulated by the OsloCTM3 before scaling for input to the CESM. We thank the reviewer for noticing that this was not specified in the figure caption. It has now been added:
"Figure SI 1: (A) Annual mean ozone concentration change from OsloCTM3 caused by global aviation NOx emissions and (B) annual mean surface temperature response to the aviation ozone perturbation scaled by a factor 40 as simulated by CESM1.2. Hatching indicates statistical significance at the 0.05 level."

The text in the manuscript has also been corrected accordingly:
"Figure SI 1A) shows the zonal annual mean ozone concentration change caused by global aviation NOx emissions from the OsloCTM3 (i.e., before scaling), while Fig. SI 1B) shows the annual mean CESM2.1 temperature response to the scaled ozone perturbation (hatching indicates statistical significance at the 0.05 level)."

Page 11, L287: But I thought above the forcing was an impulse, I.e. Non- constant?
Yes, the emission metrics ARTP(H) are pulse-based. As described in Shindell (2012), the RCSs can also be used to estimate the approximate equilibrium temperature response to a constant forcing by multiplying the sum of RCS-weighted regional RFs by the equilibrium climate sensitivity (in our study the ECS inherent in the IRF from Boucher and Reddy (2008)). We have modified the text and hope this makes it clearer:
"For comparison with climate model results, we use the regional climate sensitivities to estimate the regional equilibrium temperature response ($\Delta T_{i,r,m}$) to a constant forcing following Eq. 6 of Shindell (2012)

$$\Delta T_{i,r,m} = \sum_l RF_{l,r} \cdot RCS_{i,l,m} \cdot ECS \qquad (8)$$

and adopting the equilibrium climate sensitivity (ECS) inherent in the IRF from Boucher and Reddy (2008) described above."

Page 11, L294: This is confusing regarding emission units: since they are rationed to CO2, shouldn't they be relative to aviation CO2, then the comparison with aviation CO2 is explicit. Pardon me if that is not the appropriate definition, but I'm not sure how to interpret the very large BC GWP number.
We adopt the standard method of reporting GWPs as being relative to CO_2 and since the radiative efficiency of CO_2 (which goes into the emission metric calculations) is the same for all sources of CO_2 the reviewer's comment is not relevant. The unitless GWP and GTP of individual species is the AGWP and AGTP normalized by the $AGWP_{CO2}$ and $AGTP_{CO2}$. However, for CO_2, the radiative efficiency is the same regardless of the source. Of course, if one wants to for instance estimate the temperature response to aviation CO_2 using the $AGTP_{CO2}$, one needs to multiply by the CO_2 emissions from this sector.

Page 11, L305: But does this treat compensating LW and SW effects which are a function of surface type?
Yes it does.

Page 12, L323: Dry conditions in S. Asia? Really? In some seasons. What about the summer monsoon?
We agree with the reviewer that this may be a confusing sentence to some readers. We are referring to the high altitudes where the majority of aviation emissions occur in this region, as is noted in the first part of the sentence in question. However, drier conditions at these altitudes are not limited to this region. Furthermore, this region covers both parts of the Middle East and Arabian Peninsula, in addition to India. We have rephrased for clarification:
"(…) dominated by emissions at high altitudes (i.e., few flights landing or departing within the region), where conditions are drier (i.e., less wet scavenging of the aerosols)."

Page 13, L345: I'm not sure I agree with this. How do you deal with non local energy balances in each region?
As we noted above, the regional climate sensitivities are based on coupled climate model simulations where the perturbation is imposed separately in the four individual latitude band and the consequent temperature response averaged over each of these. Hence, these non-local energy budget terms are included.

Page 13, L364: Is it valid to apply RCS from one model to CTM results from another model? They might be vastly inconsistent, particularly in remote regions.
There are of course differences between the different chemistry-transport schemes, such as in vertical profiles of trace gases and particles or polar transport. However, we are not aware of literature that support that current models are vastly inconsistent. The reviewer's contention is not supported by any references and seems speculative.

Page 13, L370: I'm not sure the remote effects being larger make physical sense. See next comment.
Our results are supported by the existing literature. BC aerosols from aviation that are emitted in the 60-90°N region, or transported in there from lower latitudes, are located at high altitudes. Several studies have found that the efficacy of BC decreases with altitude and that in the Arctic, high altitude BC even causes a surface cooling (Flanner 2013; Ban-Weiss et al. 2011; Samset

and Myhre 2015). In the case of aviation, the contribution to temperature response in the 60-90°N region caused by within-region BC is cooling. In contrast, BC at latitudes further south warms the atmosphere locally, which in turn gives a warming impact on the Arctic transport of energy, not transport of aerosols. Since the Shindell and Faluvegi (2009), two other studies have found the same feature (Flanner 2013; Sand et al. 2013).

Studies have also shown that the relative importance of local and remote BC for the Arctic temperature response dependence on the source and/or region: BC located at lower latitudes in the Arctic have a warming impact on surface temperatures. Hence, for emissions from sectors/regions closer to or in the Arctic, the local contribution is more important (e.g., Lund et al. 2014).

While the scientific community’s understanding of the climate response to BC forcing may not yet be complete, we are not aware of published literature that disagrees with the findings of the above mentioned studies.

Page 14, L378: Here it looks like the GISS results are convolving the effect of transport with the effect of aerosols: they co-vary, but the aerosols do not cause warming. They just come in with warmer air. I think this highlights some of the problems with this methodology. I think you draw the wrong conclusion here.
If we understand this comment correctly, we think this is precisely the point behind what we (and previous analyses) argue: The remote impact is not caused by the direct warming by the aerosols, but by the transport of the air that has been warmed. See also response to comment above.

Page 14, L390: Unless emissions occur in the stratosphere, in which case contrail formation drops.
Yes, good point. We have specified this in the text.

Page 15, L406: what about significant changes in meteorology: warming reduces contrails, and also changes the tropopause height.
Yes, this is a relevant point, but it is one we addressed through the citation in the very next sentence. To clarify further we elaborate:
“Furthermore, future changes in climate may alter the meteorological and dynamical conditions, and hence affect the potential for contrail-cirrus formation in a given region (Irvine and Shine, 2015)”
We also note that the reviewer is being too simplistic – the change in tropopause height leads to a moistening of the air at a given altitude in the extratropics, and likely leads to more contrails. This point is too detailed for this paper, but our sentence deliberately refers to changes rather than specifying signs.

Page 16, L454: I’m not sure exactly what is being plotted in figure 3: please explain further and in a more detailed caption. Temperature change in each region by different emissions in each region? Are the asterix just a label for the bars or does their vertical position mean anything.
The following has been added to the caption:

“Figure 3: Regional and global mean temperature change by species and source region after A) 20 years and B) 100 years following a one-year pulse of emission from the present-day aviation sector in each source region. The asterisk shows the net temperature response in the respective latitude band for each emission source region, while the bars show the contribution from each species to the net.”

And the text has been slightly modified for clarification:
“Figure 3 shows the temperature change (net and contribution from each species) in each latitude band 20 and 100 years after a one-year pulse of present-day aviation emissions in each source region.”

Page 17, L484: If previous studies only did surface emissions (e.g. Stohl et al 2015 and Shindell 2012), then how will some of the terms from these models be valid (e.g. GISS study with RCS I think it is)?
The Stohl et al. 2015 study used the same approach as in our analysis and calculated the ARTPs for a set of components, emission source regions and seasons. They did not derive additional, new regional climate sensitivities, but compared the ARTPs with results from transient climate model runs (similar to our approach, but we consider the simulated equilibrium temperature responses). However, their emission source regions included all anthropogenic sources, i.e., mainly surface sources, and it is unclear if the conclusions from their evaluation of the ARTP can be extrapolated to the aviation sector.

Similarly, Shindell (2012) did not derive new RCS, but used those from the Shindell and Faluvegi (2009) paper and evaluated their robustness compared to historical aerosol forcing simulated by several other models. Again, total anthropogenic aerosol forcing is largely determined by emissions from surface sources, with only a small contribution from aviation.

Hence, while the application of the RCS have been evaluated in previous studies, our analysis is novel because it considers a specific sector. Neither of the abovementioned studies derived new RCS or include new results that could be directly incorporated in the current study. Furthermore, discussing the potential uncertainties in their analyses or the validity of the results is beyond the scope of our study.

Page 18, L511: I could also argue using this figure that the ARTP concept only works within the main emissions region, and is off by 50% or more relative to a physical calculation.
There are of course several ways these findings could be phrased and we could arguably explicitly say that the 28°S-28°N and 28-60°N latitude bands, where we find the best agreement, are the main emission regions. Hence, we feel that this has already been covered in the previous sections of the paper. However, since the ARTP concept is based on coupled climate model simulations, we do not agree with the interpretation in the last part of the reviewer’s argument. And that final part aside, the rest of the argument is just a different way to phrase the same findings.

Page 19, L528: I think this whole analysis highlights that the ARTP concept is very model dependent and not a general concept because of strong dependencies you have identified here.

We think it is important to separate the concept from the input data here. While the ARTP is a useful tool, and is the only emission metric to provide information at a sub-global scale, there is a certainly a need for additional studies to investigate the robustness of the regional climate sensitives. It is also a relatively new concept, and presently we do not know how model dependent the sensitivities are. As discussed in response to one of the comments above, they seem to seem fairly robust compared to the response to historical aerosol forcing. However, to further examine the model dependence it is necessary to repeat the original simulations with additional climate models, which is of course a major undertaking. What we have shown in our analysis is that there are indeed uncertainties, as well as a need for improved knowledge of vertical dependence in the forcing-response relationships, not only globally, but also in different regions. Our study presents a framework that can expanded and improved in the future when/if new, more robust and detailed estimates of regional climate sensitivities becomes available.

The ARTP has already been used in many assessments and we believe analyses such as ours are important to highlight the potential applications and associated uncertainties and point to where future studies could contribute. We also conclude that further work is needed for a more robust and general application of the concept, in agreement with the reviewer's argument.

Page 19, L546: I think you are going to have the same problem with contrails, which also have strong vertical effects, and regional forcing dependent on the climate system itself.
We agree that there may be some strong vertical effects for contrails, but at this stage this can only be speculation – unlike the case for BC where a number of pre-cursor papers already demonstrate the effect. Also the situation is quite different for BC and contrails. There is only a limited vertical domain over which contrails can physically exist, whereas there is no similar physical constraint on where the BC can be.

Page 19, L553: Can you do an uncertainty analysis here? Where are the largest uncertainties and model dependencies in the analysis.
We agree with the reviewer that a better quantification of the uncertainties is valuable. Uncertainties in ARTP arise from a number of factors, including emissions, RF and climate sensitivity. Currently, there is insufficient information to quantify the contribution from the regional climate sensitivities. Similarly, uncertainties in the aviation emission inventory are not available. We have however included an analysis of the impact of uncertainties in the different RF mechanisms and the global climate sensitivity on the global mean temperature response to the regional aviation emissions. We have also expanded the discussion on efficacy and aerosol indirect effects.

Page 21, L589: Where do you demonstrate that the response is stronger than the forcing? And how does this analysis include effects of the large scale circulation and feedbacks? You are breaking most of those feedbacks with use of a CTM and unitless response functions from another model.
This can be seen by comparing the latitudinal distribution of RF values given in Table SI2 with the distribution of the ARTPs (although the absolute magnitudes are not directly comparable since the ARTPs are given per unit emissions and as a function of time). Since we do not present the RF in separate figures and additional calculations are needed for a direct comparison of absolute values, we agree that this should be made clearer and have added (in Sect. 3.2):

“This can be seen by comparing the latitudinal distribution of the RF values given in Table SI2 with that of the ARTPs (note that absolute magnitudes are not directly comparable since the ARTPs are given per unit emissions and as a function of time).”

The effects of large-scale circulation and feedbacks are included through the use of the regional climate sensitivities (forcing-temperature response relationships), which are derived from coupled climate model simulations. See also response to previous comments.

Page 21, L606: Add to this some scaling by a factor of 40 for emissions in here somewhere, and I think this is problematic.
To clarify, it is not the emissions that are scaled by a factor 40, but the concentrations. Furthermore, this is not done in the ARTP calculations, but in the climate model simulation used for evaluation (since otherwise there is a difficulty in detecting the signal above the model-generated variability).

Page 21, L608: At least I agree with the negative conclusion here: it is not clear to me that this concept has a lot of utility for aviation. Especially since you have left out aerosol indirect effects. Anything that involves clousds I think is highly problematic using this method. Would like to see a bit more uncertainty analysis to quantify where the uncertainty lies.
Concerning the first sentence of the reviewer’s comments, we note again that it is very important to separate the concept from the characteristics of the input data we have had to use here. We believe that the concept has great utility and hopefully studies like ours will stimulate the development of more “bespoke” input data.

An important application of emissions metrics is the assessment and comparison of the impact of various components under different emissions scenarios or of emission changes following mitigation measures. This in turn provides a basis for comparing and evaluating different mitigation strategies or policies. For instance, if a mitigation measure has different effects on NOx, CO_2 or contrails, the subsequent climate impact of these species over time can be compared using our metrics. So while we agree that our frameworks has limitations when it comes to for calculating the total climate impact of aviation since we do not include indirect aerosol effects, we do not agree that there is no utility for the aviation industry. Furthermore, once established, our framework can be expanded and improved as science progresses and the knowledge of the aviation-induced forcing mechanisms is improved.

An uncertainty analysis has been added - see response to comment Page 19, L553 above.

Page 28, L882: What are the units of BC? Per unit of fuel or something else? Not clear from the caption.
BC, OC and SO_2 are per unit BC, OC and SO_2, respectively. This has been specified in the captions of both Table 1 and 2.

Page 32, L922: What are the units here? Mili-kelvin? Over what area? Do the regional colors (asterisk) correspond to the emissions colors? I’m not sure what is being plotted here.

The caption has been modified to include a more detailed description of symbols and colors (see also response to comment above). The unit (milli kelvin) is given on the y-axis and the region/area is given on the x-axis (and now specified in the caption).

Response to review of “*Emission metrics for quantifying regional climate impacts of aviation*” by Marianne T. Lund, Borgar Aamaas, Terje Berntsen, Lisa Bock, Ulrike Burkhardt, Jan S. Fuglestvedt and Keith P. Shine

We thank the reviewer for the careful review and useful comments and suggestions. Responses to individual comments are given below.

Anonymous Referee #2

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Major Comments:
142: The RF kernels of Samset and Myhre (2011) are valuable because they are vertically distributed. But they are also limited in their spatial coverage. How do the authors map between the regions in their study and those in Samset and Myhre (2011)? For example, it would seem the latter does not provide any results for the author’s SAS and SPO regions. A more complete 2D spatial mapping of aerosol direct radiative forcing efficiencies is provided in Henze et al. (ES&T, dx.doi.org/10.1021/es301993s, 2012). Perhaps results from these two studies could be combined to provide a more complete analysis? Or at least findings from the latter could be used to provide some sense of the uncertainty involved in using only the Samset and Myhre regions as the basis for the present work.
The RF kernels are calculated by applying globally uniform aerosol perturbations in each vertical layer, thereby providing full 3D fields (as already mentioned in the text), not kernels for separate geographical regions (Samset and Myhre 2011 then averages the RF globally and in different regions to illustrate geographical differences). We realize that this may not be clear from the cited literature and have added the following clarification to the methodology section in the current study:

“(..) where the radiative forcing per burden was derived by imposing globally uniform perturbations of given aerosol species at 20 different pressure levels from the surface to 20 hPa.”

A comparison of results derived by using the RF kernels and sensitivities from the adjoint modeling of Henze et al. (2012) (as well RF from full radiative transfer modeling) would be an interesting sensitivity study as in both cases RF values depend on the chemistry-transport model used to establish the background aerosol concentrations (OsloCTM2 and GEOS-chem). However, we feel that this is outside the scope of our study.

180-185: This argument feels a bit thin, given that some aspects of aerosol cloud interactions are at least better known that others. At the very least, could uncertainties owing to these processes be carried through the calculation, so that we know when uncertainties in these effect may alter the sign of the next outcome?
While we agree that the understanding of interactions between anthropogenic aerosols and liquid clouds has improved, we still maintain that the impacts of aerosols on ice clouds remain highly uncertain. Furthermore, estimates of sector specific aerosol-cloud RF remain scarce. Studies of the potential effects of aviation BC on large scale cirrus clouds have yet to agree even on the sign the radiative forcing, and the magnitude of the impact depend heavily on assumptions in the

models, ranging from -350 mW/m^2 to + 90 mW/m^2 even in a single study (Zhou and Penner 2014). Of course, if either of these number represent the actual impact, this effect would dominate the climate effect of aviation.

To our knowledge, only three studies have presented estimates of the impact of global aviation aerosols on liquid clouds, with results ranging from -46 to -15 mW/m2. We do not have the resources to quantify aerosol-cloud interactions of regional aviation emissions, but these three studies at least agree on the negative sign the global mean forcing, which could offset a considerable fraction of the warming from other components in the short term. So we have rewritten and added more detail:

"Moreover, our results do not include effects of aerosol-cloud interactions, which is an important caveat. Studies have suggested a potential impact of aviation BC on large scale cirrus clouds, but have yet to agree even on the sign of the radiative forcing (Zhou & Penner, 2014). A few studies have investigated effects of aviation emissions on liquid clouds, with global mean RF estimates ranging from -46 to -15 mW/m^2 (Gettelman & Chen, 2013; Kapadia et al., 2016; Righi et al., 2016), i.e., a cooling that could offset a considerable fraction of the positive RF of contrail-cirrus and ozone on a global scale. However, at present uncertainties in these estimates are also very large, and we consider that their inclusion here would be premature."

For Fig 4: why compare ARTP(20) and ARTP(100), when a more direct and fundamental comparison would be to just consider the RCS's? The RCS is what other people will need, if they are to use the results from this study themselves to calculate ARTPs. At the very least it would be quite useful to compare the RCS values in addition to the existing figures using ARTP in particular years.

While it is correct that the RCSs are needed as input if other people are to repeat the ARTP calculations, for instance with updated RF estimates, the ARTPs are what is needed in order to be able to make first-order estimates of the regional temperature impact of given emissions (the core application of the emission metrics). The RCS also do not have a temporal resolution, but are constant factors to distribute the impacts regionally. So, for instance the behavior of the net NOx impact over time would not be illustrated by the RCSs.

Furthermore, we have not estimated new RCSs in this study (Fig. 4 shows a comparison against temperature response to global aviation – not the response to perturbations in individual latitude bands – and only for NOx). The RCSs have been tabulated in previous literature, but to further aid the reader, we have added a summary table in the supplementary material.

General: For other people to make use of these results, it is useful to provide more information on the aviation emissions used in this study. The authors should provide a table of emissions by species and region, and they should provide separate total for emission by takeoff vs cruise altitudes. While it would be great if they could provide metrics broken down by the later category as well, I'd guess that would involve repeating a lot of calculations. But at least providing the details of the inventory they used would allow future users to be able to scale evaluations of the climate impacts of their own inventories accordingly, given some knowledge of how the authors' inventory was distributed vertically.

A table with total aviation emissions by species and region is already included in the supplementary material.

To separate metrics by cruise and landing/takeoff (LTO) operations we would indeed need to repeat our model simulations, which require additional resources and time that are not available. Guidance on how to access and use the AEDT emissions in atmospheric models is provided in a technical note by Barrett et al. (2010), including how to define and estimate emissions during LTO, allowing users to for instance use our metrics with emissions broken down by category. We have added the following:
"Guidance on how to access and use the AEDT emissions in atmospheric models is provided by Barrett et al. (2010). For input to the OsloCTM3, emissions are interpolated to the model's horizontal and vertical resolution, and averaged monthly."

Minor comments:
35-38: True, but this is evident from the fact that the RCS's in e.g. Shindell 2012 are not uniform. So it is a bit odd to place this in the abstract, although I agree the application does being attention to the issue.
The lack of one-to-one relationship between regional forcing and temperature response is one of the key features that can be emphasized by the use of sub-global, temperature-based emission metric such as the ARTP. It also points to added value of moving beyond RF-based emission metrics, such as the GWP. While this may be clear to the scientific community, it is not necessarily obvious to decision makers. We therefore feel that is an important point to highlight.

40-41: The feels a bit obvious (biggest emissions have the biggest impact) â˘A˘T would discussing the impact per emission be of more interest?
We do not feel that it is obvious that the bigger emissions lead to a largest net warming impact "in all latitude bands" (which is what we write in the abstract) as that is a result that emerges from our analysis. Since the reviewer flags this as a minor comment, we prefer to keep this as it is. To summarise the relationship between each emitting region and each response region (as shown in Figure 2) in a short sentence in the abstract would be very challenging.

66: This statement is missing references.
There are several studies of how regional emissions affect atmosphere and climate; we have added to examples – one general and one aviation specific: Berntsen et al. (2005, doi: 10.1007/s10584-006-0433-4) and Stevenson and Derwent (2009, doi: 10.1029/2009gl039422).

78: The phrase "in a grid cell" is vague (we don't know yet how big your model grid cells are) and also ambiguous with regards to whether you are referring to grid-scale changes in temperature or grid-scale changes in emissions.
The wording on line 78 is in fact "at a grid point level", which is meant to be general so as not to make the link to a specific model or resolution. The sentence also states "temperature response and other climate variables", thereby not referring to emissions. However, to clarify have rephrased to:
"(…) very detailed spatial scales (e.g., grid point level)"

83-84: Can the authors reference any in particular?

Specific measures to reduce emissions are implemented at the sectoral (as well as regional/local) level. To assess their effectiveness in terms of reducing the climate impact, one needs to know how the sector contributes to climate change to begin with. We feel that this is a very generic statement that does not require specific references.

91-93: How much uncertainty / error can this aggregation lead to?

This is not easily quantified in a general way, as it depends on, among other things, which measure, which impact and which driver is considered. For instance, in Shine et al. (2005) it was found that the net temperature response to NOx emissions was positive in the Northern Hemisphere and negative in the Southern (due to different relative importance of ozone production and methane reduction), resulting in a very small on global-mean temperature impact. Lund et al. (2012) found a factor 2-7 higher impact of aviation NOx when assuming a non-linear impact function compared with one based on global global-mean input. In terms of RF, Burkhardt and Kärcher (2011) estimated a global-mean contrail RF of 37 mW/m2, but regionally values were up to 300 mW/m2.

105-110: See also Sand et al., Nature Climate, doi:10.1038/nclimate2880, 2015.

Yes, that is a relevant reference and has been included.

183: I don’t understand what mechanisms this refers to. Please be more specific and provide references.

This refers to the existing uncertainties also for contrail-cirrus, NOx and aerosol effects considered in our study. We agree that the current wording should be improved. The sentence also fits better after the first two sentences in this paragraph and now reads:

“It should be noted that there is a broad range in the estimates of RF caused by the various aviation emissions reported in the literature (e.g., Brasseur et al. (2016); Lee et al. (2009)) and such uncertainties in RF will propagate to the emissions metrics.”

Table 1: could you list NOx in the first half at the bottom the list of species, so that it is easier to compare these numbers to the results for NOx from other studies listed below?

Good point. We have changed the order (and for consistency, also in Table 2).

Table 1: I must be missing something â˘A˘T the GTP and GWP metrics are computed by emitted species (i.e., SO2 instead of sulfate), yet the authors report values for nitrate(Table 1), and these are reported separately from NOx emissions, even though nitrate is formed secondarily in the atmospheric from NOx. Can the authors please explain this more?

We thank the reviewer for pointing this out, the tables are not labeled correctly. The NOx entry includes the impact of NOx on ozone and methane, while the nitrate label is the effect of NOx-induced nitrate formation. To make this clear, the table should read NOx-nitrate and NOx-ozone-methane. We separated out the nitrate contribution since to our knowledge no previous estimates exist, making it difficult to compare the NOx metrics with previous literature if it was included. However, we realize that this may be unclear in further application of the metrics, since these two NOx values would first have to be added. So, we have combined to one metric for the net NOx effect. Tables 1 and 2 have been changed and the text clarified:

"Our estimates also includes the cooling effect from NOx-induced formation of nitrate aerosols, which has to our knowledge not been accounted for in any previous GWP and GTP estimates."

Fig 2: Please explain the difference between the color bars vs star points in panels E and F, and define O3 vs O3PM in the figure caption itself.
This has been included in the caption.

381: Also Lacey et al. (PNAS, doi:10.1073/pnas.1612430114, 2017) used ARTPs to investigate this for cookstove emissions.
This new study of cook stove emission is very interesting, but as far as we understand it focuses on the impact of regional emissions on global temporal temperature change, determined using regional climate sensitivities, but not explicitly presenting results to support the current sentence.

132: Is this perturbation positive or negative? Does it make a difference, for SO2 and NOx?
The perturbation is negative, i.e., we remove 20% of emissions. However, the difference between the reference and perturbed run is chosen so as to determine the impact of the aviation sector emissions (rather than the impact of a specific emission increase or decrease), so in that sense it will not matter. It is possible that non-linearities in the chemistry would result in differences compared to a positive perturbation. The impact of such non-linearities when applying different size perturbations with the same magnitude has been found to be relatively small (e.g., Hoor et al. 2009; Lund et al. 2014; Myhre et al. 2011).

Fig 2: Given the factor of 0.5 in Eq 2, why isn't O3PM 50% that of the CH4 in panels E and F? Is this a consequence of the spatial re-scaling from Fry 2012? If so, I would have expected it to be less than 50% in some regions and greater than 50% in others.
This is because CH_4 includes the RF of the methane-induced stratospheric water vapor change as described in Sect. 2, while the RF O_3PM is estimated as 0.5 of the "pure" RF CH_4. We have added a clarification in the figure caption. We also discovered a very small error in a couple of the O3PM RF. These have been corrected, but do not affect our results.

222: Why not use the RCS for sulfate for sulfate, rather than for the mean of CO2 and sulfate? What RCS is used for nitrate (although not clear how nitrate is treated anyways)?
The same RCS is applied for nitrate as for sulfate and OC. This has been clarified in the text. We follow the approach of previous studies when adopting the mean sulfate/CO2 RCSs (Collins et al. 2013; Shindell and Faluvgi 2010). There has been one application with the sulfate-only RCS as well (Shindell 2012). In fact, when comparing the RCS, they are very similar (Shindell 2012 and Shindell and Faluvegi 2010), and choosing one over the other are not likely to significantly affect our findings.

492-497: This statement is a convolution of two issues that could be separated, which are that the RF of O3 per ppb is horizontally and vertically variable, and that the climate response to this RF is also variable.
A good point. We have added:
"(…) which in turn also depends on altitude (e.g., Olsen et al. (2013))."

536-538 and 550-551: Fig 4 only shows the normalized results, so it is hard to know how much of an overestimate the authors are talking about here. Can they also provide the absolute results?
The lines in question discuss the possible overestimation in more general terms, based on the existing literature on BC forcing-response. We do not currently have sufficient information on the vertical sensitivity in the BC forcing-response in latitude bands other than the Arctic to say how large such an overestimation could be. The regional distribution in Fig. 4B gives an indication, but it is only one climate model, and given the uncertainty in the magnitude in temperature response to BC in current global climate model we have some reservations against discussing the absolute magnitudes. This is further strengthened by slight differences in the experimental setup and input data in the HadSM3/ECHAM versus CESM/RTP, which, as described in the text, means that differences in absolute magnitude cannot be entirely attributed to model differences. All in all and given the scope of our study, we feel that a focus on geographical distributions is preferable.

Did the authors consider using ARTPs for the land-only response from Shindell 2012?
The reviewer brings up an interesting suggestion. A comparison of the response estimated with the land-only regional climate sensitivities against the corresponding temperature response simulated by other climate models could be an interesting part of a more detailed evaluation/sensitivity study. However, here we are limited by the availability of output from the HadSM3 and ECHAM models.

Technical corrections:
87: as a bridge
133: sulfer dioxide
137: each region are
303: in the present analysis we
Corrected.

Emission metrics for quantifying regional climate impacts of aviation

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ABSTRACT

This study examines the impacts of emissions from aviation in six source regions on global and regional temperature. We consider the NOx-induced impacts on ozone and methane, aerosols and contrail-cirrus formation, and calculate the global and regional climate metrics Global Warming Potential (GWP), Global Temperature change Potential (GTP) and Absolute Regional Temperature change Potential (ARTP). GWPs and GTPs vary by a factor 2-4 between source regions. We find the highest aviation aerosol metric values for South Asian emissions, while contrail-cirrus metrics are higher for Europe and North America, where contrail formation is prevalent, and South America plus Africa, where the optical depth is large once contrails form. The ARTP illustrate important differences in the latitudinal patterns of radiative forcing (RF) and temperature response: The temperature response in a given latitude band can be considerably stronger than suggested by the RF in that band, also emphasizing the importance of large-scale circulation impacts. To place our metrics in context, we quantify the temperature response in the four broad latitude bands following a one-year pulse emission from present-day aviation, including CO_2. Aviation over North America and Europe causes the largest net warming impact in all latitude bands, reflecting the higher air traffic activity in these regions~~here~~. Contrail-cirrus ~~For all regions, the largest single~~ gives the largest warming contribution in the short-term, but also remains important in several regions even after 100 years. CO_2 becomes dominant at a 100 year time horizon. However, our results also illustrate the relative importance of CO_2 on shorter time scales ~~is from contrail-cirrus 20 years after the emissions, while CO_2 becomes dominant at 100 years, although contrail-cirrus remain important in several regions also on this time scale~~. Our emission metrics can be further used to estimate regional temperature impact under alternative aviation emission scenarios. A first evaluation of the ARTP in the context of aviation suggests that further work to account for vertical sensitivities in the relationship between RF and temperature response would be valuable for further use of the concept.

1 INTRODUCTION

The global aviation sector has historically been one of most rapidly growing economic sectors, and the increase in activity is projected to continue in the foreseeable future. The impacts of aviation exhaust emissions on atmosphere and climate have been under scrutiny for several decades (e.g., (Brasseur et al., 2016; Fahey et al., 1995; Lee et al., 2009; Penner et al., 1999; Sausen et al., 2005). Today, global aviation contributes about 2% of the total anthropogenic CO_2 emissions. In addition to emissions of CO_2, aviation impacts climate through a number of other mechanisms, including emissions of nitrogen oxides (NOx), aerosols and precursor species, aerosol-cloud interactions and formation of contrail-cirrus. These have a much shorter lifetime than a perturbation to CO_2 and hence produce distinctly inhomogeneous radiative forcing and contribute to further inhomogeneity in temperature response. Moreover, the regional and global climate impact of equal emissions of short-lived species can vary depending on where, and even when, the emissions occur (e.g, Berntsen et al. (2006); Stevenson and Derwent (2009)). Knowledge of such regional and temporal variability is important for understanding the climate impacts of the sector and can be an important consideration in mitigation.

The spatial variability – from emissions through impacts on atmosphere and radiative forcing, to temperature response – that characterizes the aviation sector is well recognized in the scientific community. Several studies have explored the regional differences in aviation NO_x-induced ozone changes and quantified the radiative forcing (RF) of aviation emissions (Gilmore et al., 2013; Köhler et al., 2013; Lee et al., 2009; Olsen et al., 2013; Penner et al., 1999; Sausen et al., 2005; Stevenson & Derwent, 2009; Unger et al., 2013). However, fewer estimates of regional temperature response exist (Huszar et al., 2013; Jacobson et al., 2012; Olivié et al., 2012). Because of the lack of a one-to-one relationship between forcing and response patterns (Boer & Yu, 2003; Shindell et al., 2010), the strength of regional aviation-induced temperature changes cannot be inferred directly from the corresponding RF distributions. The only tools to provide temperature response and other climate variables on very detailed spatial scales (e.g., ~~a~~ grid point level) are comprehensive climate or earth system models. However, most, if not all, individual economic sectors or individual mitigation measures cause small perturbations, making it difficult (or costly) to capture a robust signal of the consequent response in climate models without significantly scaling up the emissions. On the other hand,~~-~~ knowledge~~providing first-order estimates~~ about~~of~~ contributions of individual sectors to total climate impact, and ~~or of~~ the effects of specific measures, is essential for the formulation and assessment of effective mitigation strategies.

Emission metrics, such as the Global Warming Potential (GWP) and Global Temperature change Potential (GTP) are tools which can serve as a bridge to policy making, and are commonly used for aggregating information and placing different emissions on a common scale. Several studies have also used simplified climate models to calculate the global mean temperature response to aviation (Berntsen & Fuglestvedt, 2008; Khodayari et al., 2013; Lee et al., 2009; Marais et al., 2008; Skeie et al., 2009). While aggregation and synthesis is often necessary for reasons of applicability, any such spatially aggregated measure has the disadvantage that it hides the underlying spatial distributions of impacts and the strength of regional impacts.

Recent work has advanced the development of metric concepts which can capture regional impacts. Shine et al. (2005a) and Lund et al. (2012) explored the use of non-linear damage functions to capture spatial information about climate impacts in global metrics. Lund et al. (2012) compared the impact of NOx and aerosol emissions from the transport sectors and found that the loss of information due to global averaging was largest in the case of aviation. However, currently the only metric to provide estimates of impacts on a sub-global scale is the Absolute Regional Temperature change Potential (ARTP) (Shindell & Faluvegi, 2009; Shindell & Faluvegi, 2010). The ARTP uses a set of regional climate sensitivities to provide~~s~~ time-varying surface temperature response in four latitude bands to emissions, accounting for the regional RF caused by the emissions. These sensitivities are derived from simulations with a coupled climate model and express the relationship between the pattern of a radiative forcing and the consequent surface temperature in a given latitude band. Hence, the ~~this~~ARTP provides additional insight into the geographical ~~spatial~~ distribution ~~pattern~~ of temperature change ~~response to inhomogeneous forcings~~ beyond that available from traditional global metrics. For instance, Collins et al. (2013) calculated ~~used the~~ ARTP~~s from Shindell and Faluvegi (2009) to examine the regional temperature response~~ for ~~to~~ emissions of short-lived~~near-term~~ climate forcers in four regions, while Lund et al. (2014) used the ARTP to quantify~~ied the~~ regional temperature impacts of on-road diesel emissions and Sand et al. (2016) examined Arctic temperature responses.

In this study we ~~combine chemistry-transport and radiative transfer modeling to~~ calculate ~~the~~ GWP, GTP and ARTP for global and regional aviation emissions. We consider a broad set of forcing mechanisms and emissions in six separate source regions. Aviation-induced radiative forcing of ozone and aerosols are obtained from simulations with the chemistry-transport model OsloCTM3 (Søvde et al., 2012) and subsequent radiative transfer calculations, while the radiative forcing from the formation contrail-cirrus is simulated with ECHAM5-CCMod (Bock & Burkhardt, 2016a; b). Based on this we calculate both global and regional emission metrics. This allows us to capture *(i)* the impact of regional aviation emissions on global temperature response and *(ii)* the regional temperature response to regional emissions. Using the ARTP, we quantify the regional impact of the present-day (i.e., year 2006) aviation sector, showing the contributions over time from individual species and emission regions to the temperature response in different latitude bands. The set of regional climate sensitivities that form the basis for the ARTP, by ~~is a set of regional climate sensitivities, derived by a single climate model,~~ expressing the inter-regional relationship between radiative forcings and ~~subsequent~~ temperature response~~ in the four latitude bands~~, have so far only been derived by one climate model and for four broad latitude bands (Shindell & Faluvegi, 2009). Establishing such sensitivities requires a large number of multi-decadal simulations and is thus very costly in terms of computer resources. Taking our analysis one step further, we therefore compare the regional temperature response to aviation ozone and black carbon aerosols estimated using these regional climate sensitivities with results from simulations with three other climate models, hence performing a first evaluation of the application of the ARTP in the context of selected aviation forcing mechanisms.

2 METHODOLOGY

2.1 ATMOSPHERIC CONCENTRATIONS AND RADIATIVE FORCING

To quantify the changes in atmospheric concentrations of ozone and aerosols resulting from global and regional aviation emissions, the global chemistry-transport model OsloCTM3 is used (Søvde et al., 2012). The model is run with year 2010 meteorology and a T42 resolution (approximately

2.8° x 2.8°) with 60 vertical layers from the surface to 0.1 hPa. Aviation emissions for 2006 are from the AEDT inventory (Wilkerson et al., 2010), while other anthropogenic and biomass burning emissions are from the HTAPv2 (Janssens-Maenhout et al., 2015) and Global Fire Emissions Database version 3 (GFED3; van der Werf et al. (2010)) inventories. Guidance on how to access and use the AEDT emissions in atmospheric models is provided by Barrett et al. (2010). For input to the OsloCTM3, emissions are interpolated to the model's horizontal and vertical resolution, and averaged monthly. A 20% perturbation of aviation emissions of black and organic carbon (BC, OC), sulfure ~~d oxide~~dioxide (SO_2) and NOx is applied globally and in six separate emission source regions, covering both hemispheres and the main flight corridors (Fig. 1): North America (NAM), Europe (EUR), East Asia (EAS), South Asia and Middle East (SAS), South America and Africa (SAF) and South Pacific Ocean (SPO). Total aviation emissions by species and ~~in each~~ region are~~is~~ summarized in Table SI1.

For input to the metric calculations (Sect. 2.2), we calculate the global mean RF for each emitted species *i* and emission region *r*, as well as the RF averaged over four latitude bands *l* (90-28°S, 28°S-28°N, 28-60°N and 60-90°N) ($RF_{i,l,r}$). The direct forcing of aviation aerosols is quantified using the 3D~~-dimensional~~ radiative forcing kernels developed by Samset and Myhre (2011), where the radiative forcing per burden was derived by imposing globally uniform perturbations of aerosol concentrations at 20 different pressure levels from the surface to 20 hPa. ~~while t~~The NOx-induced ozone forcing is calculated using the Oslo radiative transfer model (RTM), including stratospheric temperature adjustment. The Oslo RTM consists of a broad band scheme for longwave radiation and a scheme using the multi-stream DISORT code for shortwave radiation (Myhre et al., 2000). The RF of NOx-induced methane changes is calculated as

$$RF_{CH4,r} = \Delta\tau_{CH4,r} \cdot [CH4]_{2010} \cdot RFeff_{CH4} \cdot f \tag{1}$$

where $\Delta\tau_{CH4,r}$ is the relative change in methane lifetime between the control run and each of the emissions perturbations, $[CH4]_{2010}$ the 2010 global methane concentration of 1788 ppb, $RFeff_{CH4}$ the methane radiative efficiency of 0.36 (mW m^{-2}) ppb^{-1} (IPCC, 2014) and *f* the feedback factor of 1.34 (Holmes et al., 2013). The RF of the subsequent methane-induced O_3 change (O_3LL) (Wild et al., 2001) is calculated as:

$$RF_{O3LL,r} = 0.5 \cdot \ RF_{CH4} \tag{2}$$

A decrease in atmospheric methane also results in a slight decrease in stratospheric water vapor, and hence an additional small negative impact, included in our RF_{CH4} based on Myhre et al. (2007) as:

$$RF_{SWV,r} = 0.15 \cdot RF_{CH4} \tag{3}$$

To obtain the latitudinal distributions $RF_{CH4,l,r}$ and $RF_{O3LL,l,r}$ we use the same approach as in Collins et al. (2013) and Lund et al. (2014), and scale results according to the latitudinal distribution of methane forcing derived from a global methane concentration perturbation (Fry et al., 2012).

In order to quantify the RF from the formation and persistence of contrail-cirrus caused by global and regional aviation emissions, simulations with ECHAM5-CCMod (Bock & Burkhardt, 2016a; b) are performed at T42 resolution with 41 vertical levels using the same emission inventory and source regions as in the OsloCTM3. ECHAM5-CCMod is based on the ECHAM5-HAM (Lohmann et al., 2008), which is extended by a contrail cirrus scheme with two-moment microphysics. The two-moment microphysical scheme allows for a more realistic representation of the microphysical and optical properties of contrail cirrus. The model is validated and used to provide updated calculations of stratosphere adjusted contrail-cirrus RF by Bock and Burkhardt (2016b), resulting in a global mean RF of 56 mW m^{-2} for the 2006 AEDT aviation emissions used in this study. The existence of contrail-cirrus results in a decrease in natural cirrus clouds, causing a negative RF that partly offsets contrail-cirrus warming. The magnitude of this feedback effect is uncertain, but ~~. This cooling contribution is not included in our analysis, but is~~ estimates~~d~~ suggest a forcing ~~to be on~~ on the order of 20 percent of the RF of contrail-cirrus on global mean (Burkhardt & Kaercher, 2011). We include the feedback by reducing the contrail-cirrus RF by 20 percent for all emission source regions, i.e., assuming, in the absence of more detailed information, that the negative RF is spatially constant.

The ~~Resulting~~ RFs are given by component, source region and latitude band ~~are given~~ in Table SI2. Most of the species have short atmospheric lifetimes and consequently the RF is largest in the latitude bands closest to where the emissions occur. Some contrail-cirrus RF values are negative, which might be due to a change of cloud cover overlap in the model. It should be noted that there is a broad range in the estimates of ~~considerable uncertainties in the magnitude of~~ RF~~forcing also~~ caused by~~from~~ the various ~~other~~ aviation emissions reported in the literature ~~-induced mechanisms~~

~~remain~~(e.g., Brasseur et al. (2016); Lee et al. (2009))~~,~~ and such uncertainties in RF will ~~and~~ ~~contributes~~propagate to ~~to uncertainties in~~ the emissions metrics. To examine the importance, we perform an uncertainty analysis as described in Sect. 2.2. Moreover, ~~O~~our results do not include effects of aerosol-~~–~~cloud interactions, which is an important caveat. Studies have suggested a potential impact of aviation BC on large scale cirrus clouds, but have yet to agree even on the sign of the radiative forcing (Zhou & Penner, 2014). A few studies have investigated effects of aviation emissions on liquid clouds, with global mean RF estimates ranging from -46 to -15 mW/m^2 (Gettelman & Chen, 2013; Kapadia et al., 2016; Righi et al., 2016), i.e., a negative RF that could offset a considerable fraction of the positive RF of contrail-cirrus and ozone on a global scale. ~~This is an important limitation, as recent studies suggest that indirect effects both via the modification of cirrus clouds and low level clouds could be large .~~ However, at present uncertainties in these estimates are also very large, and we consider that their inclusion here would be premature. ~~It should be noted that considerable uncertainties in the magnitude of forcing also from other aviation-induced mechanisms remain, and contributes to uncertainties in the emissions metrics.~~

2.2 GLOBAL AND REGIONAL CLIMATE METRICS

We present calculations of the global and regional climate metrics GTP, GWP and ARTP for regional aviation emissions. The GWP and GTP methodology is extensively documented in the literature, (e.g., Aamaas et al. (2013); Fuglestvedt et al. (2003); Shine et al. (2005b)). Hence, we only describe the ARTP framework here.

The Absolute Regional Temperature change Potential (ARTP) gives the time-dependent temperature response following a pulse emission in the four latitude bands 90-28°S, 28°S-28°N, 28-60°N and 60-90°N, accounting for the regional RF caused by the emissions. This regional temperature response is calculated using a set of Regional Climate Sensitivities, $RCS_{i,l,m}$. The $RCS_{i,l,m}$ is the unitless regional response in latitude band m due to a radiative forcing in latitude band l caused by a change in species i, relative to global sensitivity. Hence, the $RCS_{i,l,m}$ express the relative regional response pattern. The regional climate sensitivities are developed based on a large set of simulations performed with the coupled atmosphere-ocean climate model GISS (Shindell & Faluvegi, 2009; Shindell & Faluvegi, 2010).

For BC, OC, SO_2, NO_x-induced ozone and contrail-cirrus, the ARTP in latitude band *m* at time *H* following a pulse emission ~~(where *H* is significantly longer than the lifetimes/adjustment times of component)~~ is calculated as:

$$ARTP_{i,r,m}(H) = \sum_l \frac{RF_{i,l,r}}{E_{i,r}} \cdot RCS_{i,l,m} \cdot IRF(H) \qquad (4)$$

where $RF_{i,l,r}$ is the RF in latitude band *l* caused by one year of emissions $E_{i,r}$ of species *i* in region *r*. The impulse response function IRF(H) is a temporal temperature response to an instantaneous unit pulse of RF, which includes the global climate sensitivity. Here we have used the IRF of Boucher and Reddy (2008), which gives an equilibrium climate sensitivity (ECS) of 1.06 K (W $m^{-2})^{-1}$, equivalent to a 3.9 K equilibrium response to a doubling of CO_2. This is in the upper range reported in the Fifth IPCC Assessment Report (Bindoff et al., 2013). Assuming that the regional climate sensitivities scale linearly with the ECS, adopting a lower value reduces the magnitude of temperature response, and its time evolution, but does not affect the latitudinal distribution.

Equation 4 can be used for short-lived species where *H* is significantly longer than the lifetime of the species (typically days to weeks). In the case of NOx-induced methane and subsequent ozone changes, the longer atmospheric residence time demands an additional IRF that describes the atmospheric decay of methane (IRF_{long}). We add:

$$IRF_{long}(t) = e^{-t/\tau} \qquad (5)$$

where τ=11.3 years is the adjustment time for methane for this model run. The $ARTP_{long}$ is then calculated following:

$$ARTP_{i,r,m,long}(H) = \sum_l \int_o^t \frac{RF_{l,r}}{E_{i,r}} \cdot IRF_{long}(t) \cdot RCS_{i,l,m} \cdot IRF(H-t)dt \qquad (6)$$

The net ARTP is the sum of contributions given by Equations 4 and 6.

The $RCS_{i,l,m}$ used in the emission metric calculations are summarized in Table SI3. For OC, sulfate, nitrate, contrail-cirrus and methane (plus methane-induced ozone changes) we use the $RCS_{i,l,m}$ of the mean of the responses to CO_2 and sulfate, as tabulated in Shindell and Faluvegi (2010). For BC and NOx-induced ozone change the respective $RCS_{i,l,m}$ from Shindell and Faluvegi (2009) (and tabulated in Collins et al. (2013)) are used.

The temperature response per unit RF can differ between different forcing mechanisms, i.e., mechanisms can have their own specific climate sensitivity parameter. This is often expressed as an efficacy, defined as the ratio of the climate sensitivity parameter for a given forcing agent to that for a given change in CO_2 (Hansen et al., 2005). The efficacy depends primarily on the spatial distribution of the RF, both in the horizontal and vertical. The $RCS_{i,l,m}$ implicitly include differences in efficacy of individual components arising from the horizontal forcing distribution (to the extent that the driving processes are accounted for in the underlying climate model simulations). The $RCS_{i,l,m}$ are established for the four forcing agents BC, ozone, sulfate and CO_2. Contrail-specific regional sensitivities do so far not exist. Two studies have indicated that the efficacy of line-shaped contrails may be as low as ~~For contrail-cirrus, an important caveat is the exclusion of efficacy (i.e., the ratio of the climate sensitivity parameter for a given forcing mechanisms to that of CO_2 changes), which studies indicate could be as low as~~ 0.3-0.6 (Ponater et al., 2005; Rap et al., 2010). However, little or no information about the efficacy of contrail-cirrus and the dependence of the climate sensitivity parameter of contrails on the horizontal forcing distribution exist. It should also be noted that efficacies from the small sector-specific forcings can currently only be derived by applying large scaling factors to produce forcings large enough to give a significant response in the climate models. This adds an additional uncertainty to deriving reliable $RCS_{i,l,m}$, in particular for contrail-cirrus due to the saturation effects. Using the average sensitivities of sulfate and CO_2 to calculate the ARTPs of contrail-cirrus allows us to account for a broader set of aviation-induced forcing mechanisms in our analysis, and these $RCS_{i,l,m}$ include both a longwave absorption and a shortwave scattering component. The efficacy of scattering aerosols and greenhouse gases is also likely less dependent on altitude than for absorbing aerosols. However, we recognize that there can be uncertainties associated with this approach that can presently not be quantified. As for estimates of efficacies at the global scale, such as those given by Ponater et al. (2005) and Rap et al. (2010), these can be included in the metric application as a scaling factor, as discussed in Sect. 3.3. However, presently few studies have investigated the efficacy of aviation-induced forcing mechanisms. ~~. While the efficacy is implicitly included in the $RCS_{i,l,m}$ of individual components, to the extent that the driving processes are accounted for the simulations from which the sensitivities are derived, we do not have specific contrail-cirrus $RCS_{i,l,m}$.~~

The dependence of the climate sensitivity parameter on the altitude of the perturbation is discussed in more detail in Sect. 3.4. We also explore potential uncertainties in our analysis arising from such vertical dependence by comparing the temperature responses estimated using the $RCS_{i,l,m}$ with temperature simulated by three additional climate models (Sect. 2.3).

Emission metrics are given on a per unit emission basis. However, for contrail-cirrus it is not clear how to pose the metric since no direct correspondence between an emission and the consequent forcing exists in this case. In order to provide consistent mass-based metrics for all components, we adopt the same approach as Fuglestvedt et al. (2010) and calculate the contrail-cirrus GWP, GTP and ARTP per unit CO_2 emitted. However, as also discussed in Fuglestvedt et al. (2010), an alternative is to relate the contrail-cirrus forcing to the distance flown. This approach may be more consistent with the way aircraft generate contrails and here we also provide metrics on a per km basis. Both approaches are problematic when applying the methodology to future air traffic scenario which likely include fuel efficiency improvements. An increase in fuel efficiency causes a higher probability of contrail formation and at the same time a decrease in CO_2 emissions. Therefore, contrail-cirrus RF per CO_2 emission would increase strongly, whereas contrail-cirrus RF per flight distance would increase less so.

In the following, we present emission metrics and calculate temperature changes for time horizons of 20 and 100 years after a one-year pulse of present-day aviation emissions. Real world emissions are of course not pulses, but rather change over time following the development in economic activity, technology and regulations. However, pulse based emission metrics can be used to quantify the net difference between two emission scenarios since any scenario can be viewed as a series of pulse emissions and analyzed through convolution (Eq. 7 below). Metrics for pulse emissions are also useful in themselves for illustrating the temporal behavior of various species. Realistic emissions will be continuous, leading to different relative contributions of short- and long-lived, warming and cooling species over time. Through the use of convolution, our metric framework can be used to estimate the temperature impact following any emission scenarios $E_{i,r}(t)$. For instance, the regional temperature response in latitude band *m* for species *i* for a scenario is the convolution of the emission scenario and the ARTP for a pulse emission (Aamaas et al., 2013):

$$\Delta T_{i,r,m}(t) = \int_0^t E_{i,r}(t') \cdot ARTP_{i,r,m}(t-t')dt' \qquad (7)$$

For most short-lived species, the result will be a scaling of the ARTP value for a certain time horizon. However, this is not the case for NOx, where the different time scales of the warming ozone effect and cooling effects linked to methane results in a change of the sign of the emission metric over time (as illustrated for GTP by Aamaas et al. (2016)).

To establish ranges in the global mean temperature change after 20 and 100 years due to uncertainty in RF and ECS, we perform a Monte Carlo analysis with 100 000 draws. Each RF mechanism is treated as a random variable, following a probability density function (PDF) defined using estimates from the existing literature. For the aerosols, we use the multi-model results from the AeroCom Phase II experiment (Myhre et al., 2013a), while for CO_2 and the NOx-induced changes in ozone and methane, we use the uncertainties from the IPCC AR5 (Myhre et al., 2013b). The NOx-induced ozone and methane impacts are assumed to be dependent and a PDF for the net RF is established. Relative uncertainties are given in Table SI4. For contrail-cirrus we infer a lognormal distribution using the best estimate of 0.05 W m^{-2} and 90% confidence interval of [0.02, 0.10] W m^{-2} based on IPCC AR5. The distribution of the total RF is derived by summing the PDFs of individual mechanisms. This approach assumes that the forcing uncertainties are independent. We also adopt a lognormal distribution for the ECS and assume a best estimate of 3 K for a doubling of CO_2, and an upper and lower value of 1.5K and 4.5K (Bindoff et al., 2013). Ranges are given at the 1 SD level (16% and 84% percentiles).

An additional source of uncertainty is the regional climate sensitivities. A full set of $RCS_{i,l,m}$ have so far only been estimated with one climate model and it can be expected that they are likely model dependent. When compared with the response to historical aerosol forcing in several other climate models, the sensitivities seem fairly robust (Shindell, 2012). Two studies have also repeated the BC experiments from Shindell and Faluvegi (2009) for BC with similar findings in terms of spatial distribution of forcing and temperature response (Flanner, 2013; Sand et al., 2013). However, this evaluation is limited and a formal quantification of the uncertainty or model dependence is currently not possible.

2.3 SIMULATED TEMPERATURE RESPONSE

To evaluate the application of the regional climate sensitivities in the context of aviation RF, we compare temperature responses estimated using the ARTP concept with temperature response patterns simulated by three climate models: the NCAR Community Earth System Model (CESM1.2) (Hurrell et al., 2013), HadSM3 (Williams et al., 2001) and ECHAM (Stenke et al., 2008). Simulations with the two latter models were performed within the EU project QUANTIFY

(Ponater et al., 2009) and results used in Lund et al. (2012). Simulations with the CESM1.2 are performed for this study using the aviation ozone concentration perturbation from OsloCTM3. In order to obtain a statistically significant response to aviation ozone in the model, the perturbation is scaled by a factor 40 (similar factors were applied in the HadSM3 and ECHAM simulations, see Lund et al. (2012) for details). We run a four member ensemble of 60 years, using the last 30 in the analysis. The statistical significance is assessed using the False Discovery Rate approach (FDR) (Wilks, 2006). Here we focus on regional patterns of temperature response, but we recognize the potential non-linearities that may arise when scaling of this magnitude is applied (e.g., Shine et al. (2012)) and uncertainties should be ~~caution~~ kept in mind when ~~that the~~considering the absolute magnitude of temperature responses ~~should be interpreted with care~~. Figure SI 1A~~)~~ shows the zonal annual mean ~~aviation induced~~ ozone concentration change caused by global aviation NOx emissions from the OsloCTM3 (i.e., before scaling)~~used in simulations with the CESM1.2~~, and while Fig. SI 1B~~)~~ shows the annual mean CESM2.1 temperature response to the scaled ~~global aviation~~ ozone perturbation (hatching indicates statistical significance at the 0.05 level).

We also compare temperature responses to aviation BC simulated by HadSM3 using the same model configuration as given in Shine et al. (2012).

For comparison with climate model results, we use the regional climate sensitivities to estimate ~~a~~the regional equilibrium temperature response ($\Delta T_{i,r,m}$) to a constant forcing ~~rather than the temperature response over time, i.e., assuming a constant forcing,~~ following Eq. 6 of Shindell (2012)~~:~~

$$\Delta T_{i,r,m} = \sum_l RF_{l,r} \cdot RCS_{i,l,m} \cdot ECS \tag{8}$$

and adopting the equilibrium climate sensitivity (ECS) inherent in the IRF from Boucher and Reddy (2008) described above.

3 RESULTS AND DISCUSSION

3.1 GLOBAL EMISSION METRICS

Tables 1 and 2 summarize the 20 and 100 year GWPs and GTPs of global and regional aviation emissions, respectively, given relative to CO_2 using the CO_2 impulse response function (IRF_{CO2})

from Joos et al. (2013). The global GWPs and GTPs are not the main focus of our study, but are included and briefly described for comparison with previous estimates. Our emission metrics do not account for climate-carbon feedbacks. If included, such feedback could increase the relative importance of non-CO_2 species (e.g., Gasser et al. (2017)).

Our GWPs for the net effect of global aviation NOx are somewhat higher than the range estimated by Skowron et al. (2013) using several different aviation emission inventories in a single model and Myhre et al. (2010) based on multi-model results (Table 1). They also fall in the upper end of the range reported by Fuglestvedt et al. (2010). The NOx GTPs fall at or in the positive end of reported ranges. A number of factors can contribute to difference in the metric values, including differences in input radiative forcing, treatment and inclusion of methane-induced changes in ozone and stratospheric water vapor, and differences in the parameters of the IRF_{CO2}. Our estimates also include the cooling effect from NOx-induced formation of nitrate aerosols, which has to our knowledge not been accounted for in any previous aviation GWP and GTP estimates. The estimated contrail-cirrus GWPs and GTPs are similar ~~about 30 percent higher than~~to those given in Fuglestvedt et al. (2010). However, values are not directly comparable as we ~~This is unsurprising since we in the present analysis~~ consider the combined RF of contrail-cirrus (i.e., young line shaped contrails and those cirrus originating from them, and their associated optical depth) and include the feedback of natural clouds in the present analysis~~, i.e., young line shaped contrails and those cirrus originating from them, and their associated optical depth, and not only line shaped contrails as in earlier studies~~. The RF of contrail-cirrus was shown to be 9 times higher than the RF of line shaped contrails when assuming constant optical depth (Burkhardt & Kaercher, 2011). Further differences arise from the use of different IRF_{CO2}. Our GWPs and GTPs for the direct effect of BC and sulfate aerosols are higher than those derived by Fuglestvedt et al. (2010) by a four (a factor two for BC GTPs). However, the values from Fuglestvedt et al. (2010) are not specific for aviation emissions, but based on input multi-model mean RF from all anthropogenic emissions (Schulz et al., 2006). ~~We are not aware of any previous estimates of aviation aerosol GWP and GTP.~~

Quantifying the GTPs and GWPs of regional aviation emissions allows us to capture how equal emissions in different locations can have different impacts on the atmospheric concentrations and RF, and in turn on global climate. Our calculations reveal considerable differences between regions for all species, and both metrics and time horizons, with a factor 2-4 (and higher for nitrate) difference between the highest and lowest metric value (Table 2). For the aerosols we generally find the largest magnitude GWPs and GTPs for South Asia (SAS) emissions, followed by South America and Africa (SAF) or South Pacific Ocean (SPO). The high values for the SAS region reflects a relatively long lifetime of the aerosols here compared to other emission regions. This, in turn, is likely caused by a combination of the underlying distribution of emissions, which is dominated by emissions at high altitude~~s emissions~~ (i.e., few flights landing or departing within the region), where~~, and the dry~~ conditions are drier (i.e., less wet scavenging of the aerosols) ~~in the region~~. For NOx, the values are highest for SPO, while for contrail-cirrus we find high values for aviation over NAM and Europe (EUR), where conditions for contrail formation is prevalent (e.g., Burkhardt et al. (2008); Irvine and Shine (2015)) and for SAF (see more detailed discussion in Sect. 3.2). From a policy perspective, knowledge of such regional differences is important if metrics are used to quantify the climate impact of emissions or emission changes in cases where there is a simultaneous change in the geographical emission distribution, or if used to evaluate the effect of implementing measures to reduce emissions in different regions.

While several studies have estimated GWPs and GTPs for global aviation NOx emissions, as discussed above, few have produced estimates for regional aviation emissions. Köhler et al. (2013) quantified the climate impact of aviation emissions in North America, Europe, India and China. The reported GWP(20)~~s and GTP(100) for emissions in India~~ agree within 10-~~15~~30 percent with estimates for all regions ~~SAS~~ in the present analysis, while ~~. O~~our GTP(20) values are about 50 percent lower in absolute magnitude for all emission regions, and ~~whil~~e GWP(100) and GTP(100) for NAM and EUR are 50-100 percent higher than Köhler et al. (2013) estimates. Again it should be noted that these difference can be caused by a number of factors. Moreover, because the two studies use differently defined emission source regions, only a rough comparison is possible.

3.2 REGIONAL EMISSION METRICS

While GWPs and GTPs illustrate how equal emissions in various regions can have different impacts on global climate, they can naturally not inform us of the actual regional distribution of impacts. The ARTP allows us to estimate temperature impacts with at least some spatial information.

Figure 2 shows the ARTP with a time horizon of 20 years (ARTP(20)) for BC, OC, SO_2 and contrail-cirrus for each emission source region, and the ARTP(20) and ARTP(100) of aviation NOx. We do not show ARTP(100) for aerosols and contrail-cirrus here. The absolute values decay strongly over time, but the latitudinal patterns will be identical on both time horizons. Results for global aviation emissions are given in the SI, as are contrail-cirrus metrics on a per km-basis.

For OC and SO_2 (Fig. 2B and C), we calculate the highest magnitude ARTP(20) (i.e., temperature impact per unit emission) for aviation in SAS in all latitude bands except 90-28°S, where values for SAF and SPO are slightly higher. Excluding the SAS region, aviation in EUR and NAM give the highest temperature impact per unit emission in the 28-60°N and 60-90°N regions, which is also where the corresponding RF is strongest (Table SI-2). This is unsurprising given that these species are short-lived and the forcing they exert are largely localized to the emission region. However, using the ARTP reveals important differences between the latitudinal distribution of RF and subsequent temperature response. In given latitude bands, the temperature impact can be considerably stronger than the RF in that band suggests, and can extend to the opposite hemisphere to where the emissions occurred. This can be seen by comparing the latitudinal distribution of the RF values given in Table SI2 with that of the ARTPs (note that absolute magnitudes are not directly comparable since the ARTPs are given per unit emissions and as a function of time). Applying the $RCS_{i,l,m}$ given in the coarse latitude bands smooths out the impacts such that there is less latitudinal variation in the temperature responses than in the RFs. This illustrates the dependence of temperature response on both forcing exerted locally and on remote impacts through large-scale circulation impacts and feedbacks in the climate system.

The latter effects are also very important in the case of BC (Fig. 2A). Again, the ARTP(20) is highest for aviation in SAS, while the difference between remaining regions is smaller than for OC and SO_2 in most latitudes bands. In the 60-90°N region, aviation in the Southern Hemispheric regions cause the highest temperature per unit emissions, despite being far removed from the Arctic. In the GISS results, the Arctic temperature response to local (i.e., within Arctic) forcing is in fact negative (Shindell & Faluvegi, 2009). This local cooling effect applies to BC changes in the mid to upper Arctic troposphere, which is where aviation is most important. Aviation BC emissions in EUR and NAM are more easily transported into the Arctic region and hence induce a stronger local forcing and in turn a larger surface cooling. The net effect of aviation in these regions on the Arctic is still a warming, but this warming is partly offset by the cooling contribution from within Arctic RF. In contrast, aviation BC emissions in SAS, EAS, SAF and SPO have less potential for long-range transport to the Arctic, but the remote BC forcing warms the Arctic through transport of energy. In terms of mitigation, these results underline that if the goal is to limit temperature increase e.g., in the Arctic, it is necessary to go beyond radiative forcing as an indicator and to also consider the impact of emission in more remote regions. This feature has been illustrated also for other sectors and regions (Collins et al., 2013; Lund et al., 2014).

For contrail-cirrus (Fig 2D), the ARTP(20) for aviation in EUR and NAM is substantially larger in the 28-60°N and 60-90°N latitude bands than for other sources regions considered in this study, while the difference between source regions is less pronounced in the Southern Hemisphere latitude bands. There are two main competing processes at play. Contrail formation is generally more prevalent in the extratropics due to lower temperatures at flight levels than in the tropics and may persist longer due to larger probability of ice supersaturation. An upward shift in the flight level in the tropical troposphere increases the probability of contrails formation and ice supersaturation (Burkhardt et al., 2008). ~~It should be noted that l~~Local peaks of ice supersaturation are also found in the tropics (Irvine & Shine, 2015), in fact the probability of ice supersaturation is highest in the upper tropical troposphere (Lamquin et al., 2012). Furthermore, once contrails have formed~~ contrail-cirrus~~, the optical depth of contrail-cirrus is higher in the tropics due to the larger amount of water vapor available for deposition. This higher optical depth in the tropics and the consequently higher RF has also been found in contrail-cirrus simulations (Burkhardt & Kaercher, 2011). However, none of our source regions cover only the tropics. In the SAS region, the air is mostly too warm for contrail formation. However, if contrails were present here, their radiative forcing efficiency would be high. Due to the competing short- and long-wave effects, there can be important diurnal and seasonal variability in the net impact of contrail-cirrus (e.g., Stuber et al. (2006); Bock and Burkhardt (2016b)). The diurnal effects depend~~s~~ on assumptions about the contrail-cirrus lifetime and were shown to be small (Newinger & Burkhardt, 2012) when using the contrail-cirrus parameterization of Burkhardt and Kaercher (2011). This effect is not captured in our analysis using annual mean RF as input.

It should be emphasized that the contrail-cirrus metrics are suitable for the average of the present-day aircraft fleet. Their application would not be appropriate if there are significant changes in routes and flight altitudes. Furthermore, future changes in climate may alter the meteorological and dynamical conditions, and hence ~~also~~ affect the potential for contrail-cirrus formation in a given region (Irvine & Shine, 2015). As discussed in Sect. 2, several factors contribute to uncertainty in the emission metrics, and should be kept in mind in further applications.

The ARTP of aviation NOx (Fig. 2E, F) is separated into contributions from ozone, methane and methane-induced ozone, as well as the direct effect of nitrate aerosols. The stars indicate the net NOx effect. The ARTP(20) is negative in all but two cases, i.e., the net effect of one year of aviation NOx emissions is a cooling on this time scale, dominated by the NOx-induced methane loss. However, it is important to note that the sign and magnitude of the net NOx effect is very sensitive to the choice of time horizon due to the very different time scales on which the ozone and methane contributions act. In particular, during the first decade after emission, the strong but short-lived warming from ozone dominates, resulting in a net positive effect (see also Fig. 6B of Fuglestvedt et al. (2010)). Moreover, the NOx ARTP is also influenced by the spatial patterns of ozone and methane. Due to the shorter lifetime, the aviation-induced ozone perturbation is more heterogeneous than the methane concentration change, and more confined to the emission source region. The choice of time horizon may therefore affect both the net NOx effect and the relative importance of source regions. Both the impact of changes in ozone and methane from a pulse emission on NOx decays strongly over time, as reflected by the much smaller ARTP(100). While the methane cooling remains important on longer time scales, the absolute magnitude diminishes strongly towards a time horizon of 100 years. For all source regions, the competing effects of ozone warming and methane cooling over time results in a small, but net positive global mean effect of aviation NOx on a 100 year time horizon. In the 90-28°S latitude band the ARTP(100) is positive for emissions occurring in the Southern Hemisphere, but negative for emissions in the Northern Hemisphere, as the latter causes a much smaller ozone concentration change in this latitude band and the methane cooling becomes relatively more important over time. A similar response is seen in the 60-90°N latitude band.

3.3 REGIONAL CLIMATE IMPACTS OF THE PRESENT-DAY AVIATION SECTOR

To place our climate metrics in context and illustrate further application, we apply the ARTP and estimate the regional temperature responses over time to present-day aviation in the six emission source regions. Figure 3 shows the ~~contribution to~~ temperature change~~response~~ (net and contribution from each species) in each latitude band ~~by species and emission region~~ 20 and 100 years after a *one-year pulse* of present-day aviation emissions in each source region. The current aviation climate mitigation policy is largely focused on CO_2. The contributions from aviation CO_2 emissions are~~is~~ therefore added to place the impact of short-lived and long-lived species in context. The error bars show the 1 SD ranges due to uncertainties in RF and ECS (see Sect. 2.2). Because the same relative uncertainty is assumed for emissions in all source regions and our analysis does not account for uncertainty in the regional climate sensitivities, we only include the ranges in the global mean temperature change.

The majority of flights today take place over the northern mid-latitudes. As a result, the net warming is largest in all latitude bands for emissions over NAM and EUR. On a 20 year time horizon, the largest warming contribution from these source regions comes from contrail-cirrus formation and, despite the highly localized RF, the temperature impact is not only limited to the latitude band closest to where the emissions occur. ~~As noted in Sect. 2.2, studies indicate that the efficacy of contrail-cirrus may be lower than one.~~ ~~This is not accounted for in the current analysis, but adopting a uniform efficacy of e.g., 0.6 (Ponater et al., 2005) would result in a 40 percent lower contrail-cirrus impact across all latitude bands.~~ The net warming is slightly offset by a small cooling due to NOx-induced methane loss, especially in the 90-28°S and 60-90°N regions. As pointed out above, the sign and magnitude of the net NOx effect depends strongly on the chosen time horizon. For instance, on a 10 year time horizon (not shown here), the net NOx response is a warming in the 28°S-28°N and 28-60°N regions for emissions in NAM, EUR and EAS. Aviation emissions of BC are small and therefore contribute little to the net impact, despite the strong efficiency (i.e., temperature change per kg emitted).

Even on short time horizons (e.g., 20 years), the warming contribution from CO_2 is important. For emissions in EAS, SAF, SAS and SPO, CO_2 is of comparable magnitude to contrail-cirrus after 20 years. On longer time horizons (e.g., 100 years) ~~the impact from contrail-cirrus and NOx decays, and~~ the CO_2 contribution becomes dominant in all latitude bands. This has previously been illustrated for the global mean temperature impact of the sector (Berntsen & Fuglestvedt, 2008). Because the perturbation in CO_2 is longer-lived and well-mixed, the warming in the Southern Hemisphere becomes relatively more important compared to the other latitude bands on longer time scales. Nevertheless, for emissions in NAM and EUR, for the northern hemisphere response regions and the global mean, the contributions from contrail-cirrus remains substantial and approximately 10-20 percent of the CO_2 response, even on these long time scales. Figure 3 also shows that the relative importance of the source regions across latitude bands following a pulse emission changes very little over time. However, these calculations do not account for potential future changes in the geographical distribution of emissions.

The considerable uncertainty in the aviation-induced forcing mechanisms and climate sensitivity is reflected in the error bars. After 100 years, the uncertainty in climate sensitivity dominates as the relative contribution from the more uncertain, but short-lived mechanisms decays and CO_2 becomes more important. Note that the same relative uncertainties apply to all source regions. For contrail-cirrus, an additional source of uncertainty is the efficacy. As noted in Sect. 2.2, studies indicate that the efficacy of contrail-cirrus may be lower than one. Because only two estimates exist in the literature, efficacy is not included in present analysis. However, adopting a spatially uniform efficacy of e.g., 0.6 (Ponater et al., 2005) would result in a 40 percent lower contrail-cirrus impact across all latitude bands.

Our study focuses on the pulse based emission metrics and does not consider the future temperature impact of aviation following *emission scenarios*, which would change the timescale of the response and the relative importance of short- and long-lived species over time. As described in Sect. 2.2, our pulse based emission metrics can be used in further studies to investigate the regional temperature impacts following more realistic emission scenarios. For instance, as the simplest form of scenario, one could assume that emissions are kept constant at the present-day level. In this case, the contributions from short-lived species such as contrail-cirrus, ozone and sulfate would quickly become sustained at a constant level rather than decay towards zero and the warming from CO_2 would gradually accumulate (e.g., Berntsen and Fuglestvedt (2008)). The impact of contrail-cirrus may even increase if emissions are kept constant while fuel efficiency is improved. The temporal behavior of total net temperature response, as well as the net NOx effect, would differ notably from the pulse emission case.

3.4 EVALUATION

Several studies have calculated ~~used the~~ ARTPs ~~concept to estimate temperature responses to~~for emissions from specific sectors or regions (Collins et al., 2013; Lund et al., 2014; Sand et al., 2016; Stohl et al., 2015). Stohl et al. (2015) also compared the estimated regional temperature responses to short-lived climate pollutants with ~~to~~ those simulated by several climate models. However, these studies focus only on surface sources and the evaluation may not be valid for aviation. ~~Moreover, t~~The regional climate sensitivities that form the basis for the ARTP calculations are derived from simulations with only one climate model. Moreover, the~~They~~ sensitivities are~~ also~~ representative of the response to a vertical forcing profile resulting from total anthropogenic emissions, i.e., one that in many regions differ considerably from those induced by the mainly high-altitude aviation emissions. Several recent studies have found a strong vertical sensitivity in the BC forcing-response relationship, with decreasing efficacy with altitude (Ban-Weiss et al., 2011; Flanner, 2013; Samset & Myhre, 2015). Climate model studies also indicate that the forcing-response relationship for ozone will be dependent on both the vertical and horizontal distribution of the ozone change (Berntsen et al., 1997; Hansen et al., 1997; Joshi et al., 2003), which in turn also depends on altitude (e.g., Olsen et al. (2013)). As discussed in Sect. 2.2, a formal quantification of uncertainties in the regional climate sensitivities is currently not possible. However, ~~I~~in ~~the~~ light of the potential uncertainties arising from ~~such~~the ~~–~~vertical dependence~~y~~, we perform a first evaluation of the ARTP concept in the context of aviation ozone and BC. Further evaluation, especially of contrail-cirrus, would be valuable, but require resources beyond those available for the currrent study. ~~However, the resources for the required climate model simulations were not available for this study.~~

Figure 4A shows the normalized regional temperature response to aviation ozone, as simulated by the CESM1.2, HadSM3 and ECHAM (see Sect. 2.3) and estimated using the regional climate sensitivities that form the basis for the ARTP concept. There are several factors potentially contributing to differences in the absolute magnitude of temperature responses in the simulations, including differences in the ozone concentration perturbation resulting from differences in emissions or ozone change per unit emission, radiative efficiency and ECS. HadSM3 and ECHAM used the multi-model average ozone concentration change resulting from year 2000 aviation NOx emission (0.67 TgN) (Hoor et al., 2009), while this study (using CESM2.1) uses the ozone change simulated by one model (OsloCTM3) and year 2006 aviation emissions (0.81 TgN). Based on visual inspection, these two aviation-induced ozone concentration perturbations are quite similar, with slightly larger perturbation at high northern latitudes in the present study. Nonetheless, here we focus on the spatial pattern across latitude bands rather than absolute magnitudes and therefore normalize the temperature response in each band by the respective global mean response.

The climate models and RTP agree reasonably well in the 28°S-28°N and 28-60°N latitude bands. However, in both the 90-28°S and 60-90°N regions, the temperature response simulated directly by the climate models is considerably higher than that estimated using the ARTP. The low ARTP-derived temperature response in the 60-90°N region reflects the low sensitivity in the GISS model in this latitude band to ozone forcing exerted both locally, as well as in the 28-60°N region where the aviation-induced forcing is highest (Fig. 1 of Shindell and Faluvegi (2009)). A low, and even negative, sensitivity to Northern Hemisphere forcing also characterizes the 90-28°S band.

The reason for the low sensitivity in the GISS simulations, or whether this is a feature specific to this model, is not clear. It is possible that the differences between modeled and estimated temperature response to aviation ozone forcing can be at least partly explained by vertical variations in the response to ozone perturbations. Early work by Hansen et al. (1997) suggested a surface cooling in response to a global near surface ozone perturbation and a maximum efficacy around 700-800 hPa, followed by a decreasing efficacy for ozone perturbations in the upper troposphere. The latter was supported by Joshi et al. (2003). However, the increased sensitivity to lower stratosphere perturbations found by Joshi et al. (2003) was not seen in the Hansen et al. (1997) results. Such uncertainties in the efficacy around the UTLS region are important in the case of aviation.

Figure 4B compares aviation BC temperature response to that obtained from the HadSM3. The regional distribution across latitude bands is similar for the estimated and simulated temperature response. However, here we only have temperature response simulated by one climate model. Given the substantial uncertainty and inter-model differences in model estimates of BC climate impacts (Baker et al., 2015; Samset et al., 2014; Stohl et al., 2015), additional model simulations are needed for further comparison and evaluation.

The notable decrease in BC efficacy with altitude globally, and particularly at high latitudes (Ban-Weiss et al., 2011; Flanner, 2013; Samset & Myhre, 2015), raises the question whether using the ARTP to estimate temperature responses to the high-altitude aviation BC forcing could result in an overestimation of the absolute magnitude. Flanner (2013) provided vertically resolved climate sensitivities for the Arctic temperature response to local Arctic BC forcing. Using these, Lund et al. (2014) found important differences in the temperature response to BC from on-road transportation in the 60-90°N latitude band compared to using the single regional climate sensitivity derived from Shindell and Faluvegi (2009) (and used in the present analysis). At the altitudes in the 60-90°N region where the aviation-induced RF peaks, the regional climate sensitivity from Flanner (2013) and Shindell and Faluvegi (2009), and hence the estimated temperature response, agree quite well. This agreement may not hold for all regions, but similar vertically resolved climate sensitivities for other latitude bands or species do not currently exist.

Based on our analysis, some care is needed when using the ARTP in the context of aviation emissions. Specifically, our findings suggest that the temperature response in the 90-28°S and 60-90°N regions to aviation ozone could be underestimated by the regional climate sensitivities currently used in the ARTP calculations. Furthermore, a possible overestimation of temperature response to aviation BC can not be ruled out. Further work to quantify the importance of vertical variations in forcing-response relationships and develop regional climate sensitivities based on vertically-resolved forcing perturbations would be valuable for future use of the ARTP.

4 CONCLUSIONS

We have examined the impacts of aviation emissions on global and regional temperature, characterizing them using emission metrics. We address the impacts of NO_x on ozone and methane, aerosols and contrail-cirrus formation, and consider six emission regions spanning both hemispheres. In addition to updated emission metrics for global aviation, we present GWPs and GTPs on 20 and 100 year time horizons for a larger set of species and regions than previous studies. We also calculate the Absolute Regional Temperature change Potential (ARTP) for aviation, allowing us to not only capture how equal emissions in different regions impact global climate, but also quantify the temperature impacts on a sub-global scale.

The metric values depend significantly on emission regions. In the case of aviation aerosols, we calculate the highest GWPs and GTPs for emissions in South Asia, followed by South America and Africa, and the South Pacific Ocean. The strong efficiency of emissions over our South Asian region reflects a relatively long lifetime of the aerosols here compared to other region. Our results do not include aerosol-cloud interactions, an important limitation as recent studies suggest aviation can potentially have strong impact through modification of both cirrus and low-level clouds; ~~,~~however~~ although~~ this contribution remains particularly uncertain. The net temperature impact over time following a pulse emission of aviation NOx is determined by the relative importance of the cooling and warming methane and ozone contributions, and is very sensitive to the choice of time horizon. The net NOx ARTP is negative after 20 years and switches to a small net warming on a 100 year time horizon on global mean and in the latitude band closest to the where the emission occur. Metrics for contrail-cirrus are calculated on a per unit emission of aviation CO_2 basis. The GWPs and GTPs are highest for North America and Europe, where contrail-cirrus formation is prevalent. However, once formed, contrail-cirrus in the tropics have much higher optical depth due to the larger amount of water vapor. The metric values do not account for a lower efficacy of contrail-cirrus that has been suggested by previous studies, but remains highly uncertain. Moreover, the contrail-cirrus metrics would not be appropriate if there are significant changes in routes and flight altitudes, or if changes in climate or propulsion efficiency affect the potential for contrail-cirrus formation.

The ARTPs illustrate how the latitudinal temperature pattern can differ significantly from the global mean, as well as from the latitudinal pattern of RF. Due to the short lifetime of many of the aviation forcing mechanisms, the RF is typically largely confined to the latitude band closest to where the emissions occur. However, in a given latitude band, the temperature response can be considerably stronger than suggested by the corresponding forcing, emphasizing the importance of both forcing exerted locally and remote impacts through large-scale circulation impacts and feedbacks in the climate system.

While the strongest ~~efficiency (~~temperature change per unit~~kg~~ aerosol and NOx emitted~~) of aviation aerosols and NOx~~ is found for aviation ~~emissions in~~over the South Asian region in our study, the majority of flights today take place over the northern mid-latitudes. The net warming impact 20 and 100 years following a one-year pulse emission from the present-day aviation sector is therefore largest in all latitude bands for emissions in North America and Europe, with ~~. For all regions,~~ the largest warming contribution after 20 years ~~is~~ from contrail-cirrus ~~on a 20 year time horizon~~. Furthermore, contributions from contrail-cirrus remain important at the 10-20 percent of CO$_2$ level in several regions even on a time horizon of 100 years. The discussion around CO$_2$ often focuses on its long-term impacts. Our results illustrate that while CO$_2$ is dominant on longer time scales, it also gives a considerable warming contribution already after 20 years. ~~While CO$_2$ becomes dominant on the 100 year time horizon, contributions from contrail-cirrus remains important on the 20 percent of CO$_2$ level in several regions even on these long time scales.~~ Our metric framework can also be applied to estimate future regional temperature impact of more realistic emissions scenarios for the sector, which would influence the temporal characteristic of the response and the relative contributions of short and long-lived species over time.

While the ARTP concept is an important and useful tool for providing first order estimates of regional temperature of various emissions, our analysis indicate that some care is needed when it is used in the context of aviation emissions, or more generally, in situations that differ significantly from those used to derive the regional climate sensitivities for the ARTP calculations in the first place. In particular, further work to quantify and account for the relationship between vertically-resolved radiative forcing perturbations and surface temperature response is needed to allow for a more general applicability of the concept.

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Tables

Table 1: GWP and GTP of global aviation emissions for time horizons 20 and 100 years. Values are given on a per unit aviation emission basis (per kg BC, OC and SO_2, respectively, while contrail-cirrus is calculated per kg aviation CO_2, and NOx ~~and nitrate~~ per kg N). The GTPs are calculated using the impulse response function by Boucher and Reddy (2008). For comparison, aviation NOx GWP and GTP values from three previous studies are also included.

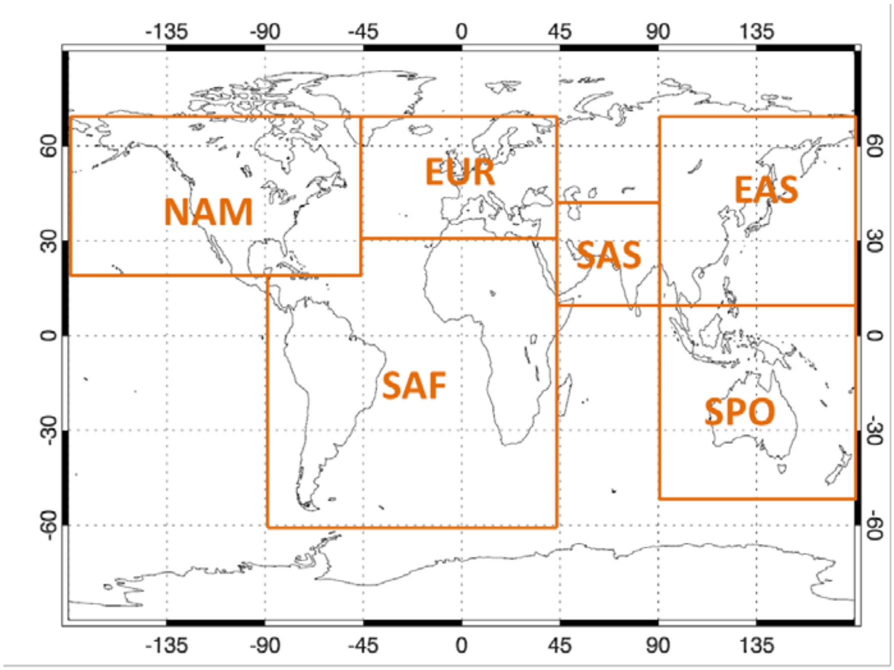
	GWP		**GTP**	
Component	**H=20**	**H=100**	**H=20**	**H=100**
Contrail-cirrus	3.1	0.84	0.93	0.12
BC	3911	1064	1135	147
SO_2	-559	-152	-162	-21
~~**Nitrate**~~	~~-16~~	~~-4.3~~	~~-4.6~~	~~-0.59~~
OC	-282	-77	-82	-11
NOx	411	77	-138	9
NOx				
Fuglesvedt et al. (2010)	120 to 470	-2.1 to 71	-590 to -200	-9.5 to 7.6
Myhre et al. (2011)	92 to 338	-21 to 67	-396 to -121	-5.8 to 7.9
Skowron et al. (2013)	142 to 332	4 to 60		

Table 2: GWP and GTP of regional aviation emissions for time horizons 20 and 100 years. Values are given on a per unit aviation emission basis (per kg BC, OC and SO_2, respectively, while

contrail-cirrus is per kg CO_2, and NOx ~~and nitrate~~ per kg N). The GTPs are calculated using the impulse response function by Boucher and Reddy (2008).

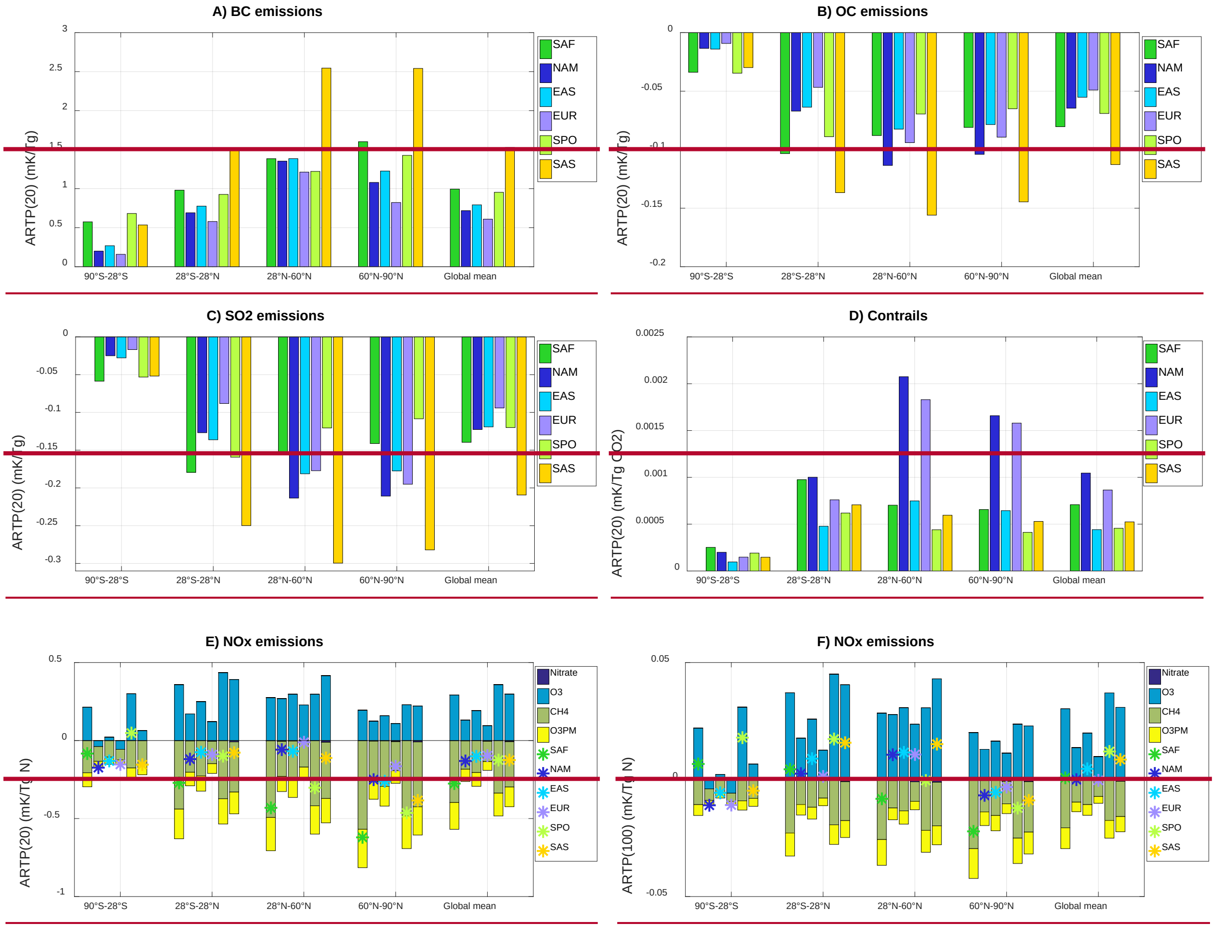
		GWP		GTP	
Component	**Source region**	**H=20**	**H=100**	**H=20**	**H=100**
Contrail-cirrus	SAF	3.6	0.99	1.09	0.14
	NAM	3.3	0.90	1.00	0.13
	EAS	1.7	0.45	0.50	0.06
	EUR	2.5	0.67	0.75	0.10
	SPO	2.3	0.63	0.70	0.09
	SAS	2.6	0.70	0.78	0.10
OC	SAF	-481	-131	-140	-18
	NAM	-289	-79	-84	-11
	EAS	-283	-77	-82	-11
	EUR	-197	-54	-57	-7.4
	SPO	-419	-114	-122	-16
	SAS	-611	-166	-177	-23
BC	SAF	5420	1470	1570	203
	NAM	3560	969	1030	133
	EAS	4170	1140	1210	156
	EUR	2300	816	871	112
	SPO	4940	1340	1430	185
	SAS	8250	2250	2390	309
SO2	SAF	-833	-227	-242	-31
	NAM	-550	-150	-159	-21
	EAS	-602	-164	-175	-23
	EUR	-378	-103	-110	-14
	SPO	-746	-203	-216	-28
	SAS	-1120	-304	-324	-42
~~**Nitrate**~~	~~SAF~~	~~-8.6~~	~~-2.3~~	~~-2.5~~	~~-0.32~~
	~~NAM~~	~~-13~~	~~-3.4~~	~~-3.7~~	~~-0.47~~
	~~EAS~~	~~-7.4~~	~~-2.0~~	~~-2.1~~	~~-0.28~~
	~~EUR~~	~~-20~~	~~-5.5~~	~~-5.9~~	~~-0.76~~
	~~SPO~~	~~-3.3~~	~~-0.89~~	~~-0.95~~	~~-0.12~~
	~~SAS~~	~~-39~~	~~-11~~	~~-11~~	~~-1.5~~
NOx	SAF	484	70	-316	6.26
	NAM	280	48	-126	5.0
	EAS	513	108	-79	13
	EUR	210	37	-87	4.0
	SPO	806	159	-205	19
	SAS	695	137	-176	16

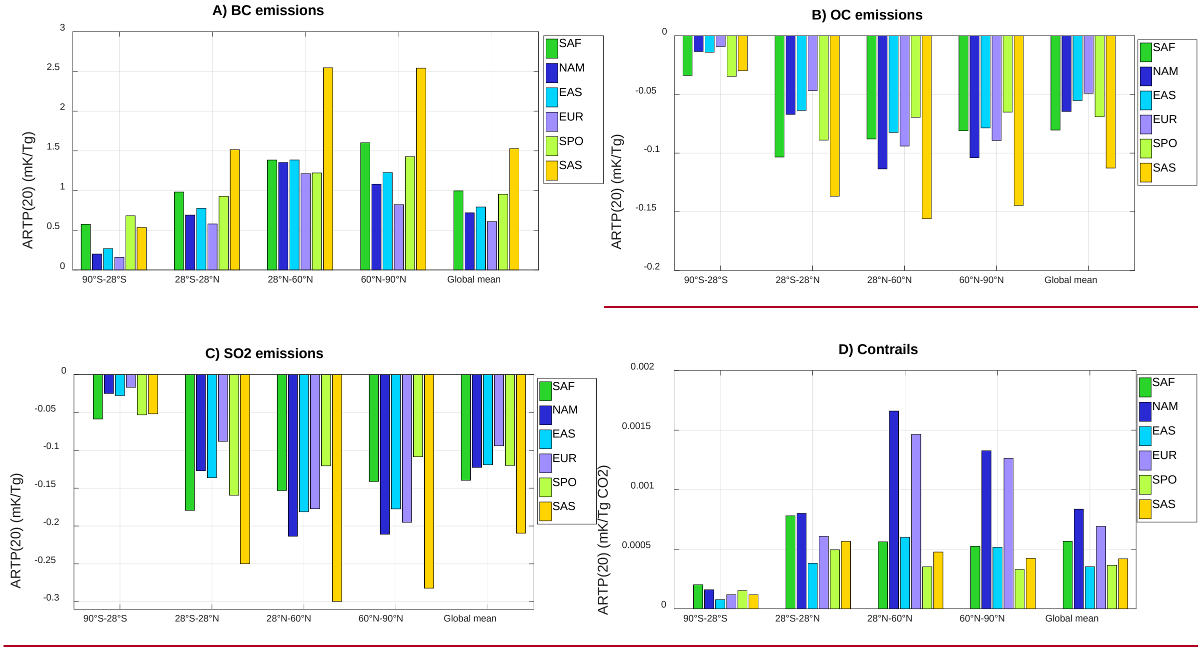
Figures



NAM = North America, EUR = Europe, SAS = South Asia and Middle East, EAS = East Asia, SAF = South America and Africa, SPO = South Pacific Ocean

Figure 1: Definition of emission source regions in this study.


A) BC emissions
ARTP(20) (mK/Tg)
3
2.5
2
1.5
1
0.5
0
90°S-28°S
28°S-28°N
28°N-60°N
60°N-90°N
Global mean
SAF
NAM
EAS
EUR
SPO
SAS
B) OC emissions
ARTP(20) (mK/Tg)
0
-0.05
-0.1
-0.15
-0.2
C) SO2 emissions
ARTP(20) (mK/Tg)
-0.25
-0.3
D) Contrails
ARTP(20) (mK/Tg CO2)
0.0025
0.002
0.0015
0.001
0.0005
E) NOx emissions
ARTP(20) (mK/Tg N)
-0.5
-1
Nitrate
O3
CH4
O3PM
F) NOx emissions
ARTP(100) (mK/Tg N)
0.05
-0.05


A) BC emissions
ARTP(20) (mK/Tg)
3
2.5
2
1.5
1
0.5
0
90°S-28°S
28°S-28°N
28°N-60°N
60°N-90°N
Global mean
SAF
NAM
EAS
EUR
SPO
SAS
B) OC emissions
ARTP(20) (mK/Tg)
0
-0.05
-0.1
-0.15
-0.2
C) SO2 emissions
ARTP(20) (mK/Tg)
-0.25
-0.3
D) Contrails
ARTP(20) (mK/Tg CO2)
0.002
0.0015
0.001
0.0005

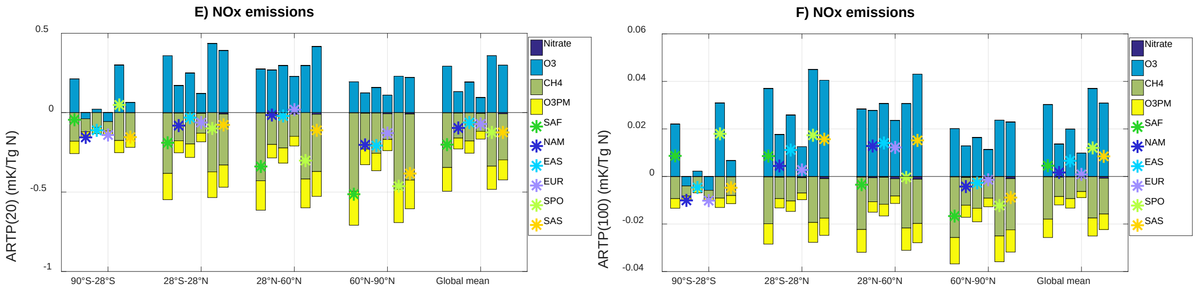


Figure 2: ARTP(20) of aviation (A) BC, (B) OC, (C) SO_2 and (D) aviation-induced contrail-cirrus, and (E,F) ARTP(20) and ARTP(100) of aviation NOx. The asterisk in panels E and F show the net NOx effect of emissions in each source region, while the colored bars give the contributions from ozone production (O_3), NOx-induced methane loss (CH_4) (including subsequent stratospheric water vapor loss), methane-induced ozone changes (O_3PM) and NOx-induced nitrate formation.

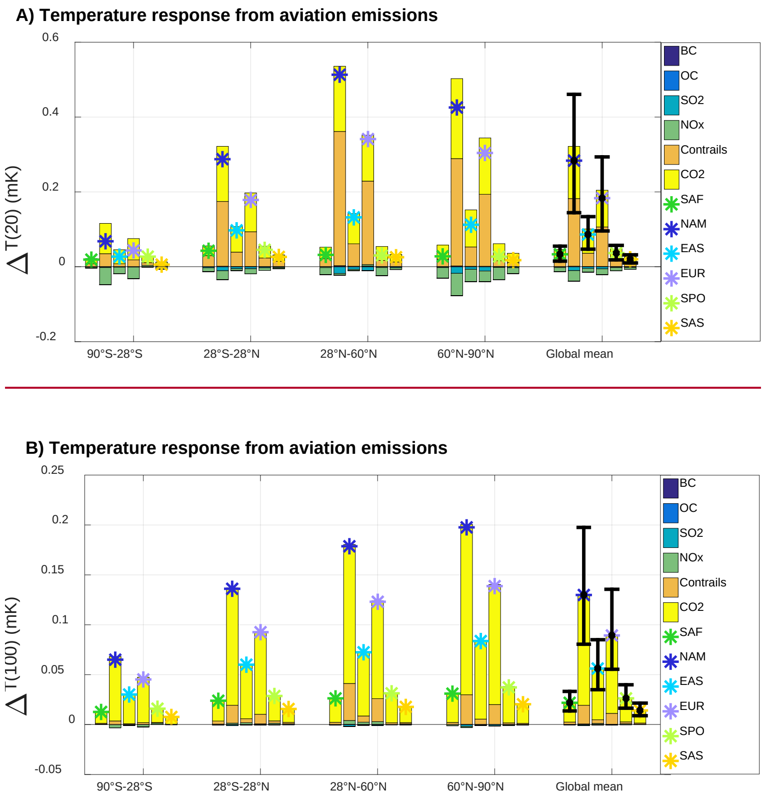


Figure 3: Regional and global mean temperature change~~response~~ by species and source region after A) 20 years and B) 100 years following a one-year pulse of emission from the present-day aviation sector in each source region. The asterisk shows the net temperature response in the respective latitude band for each emission source region, while the bars show the contribution from each species to the net. Error bars show the 1 SD ranges due to uncertainties in RF and ECS.

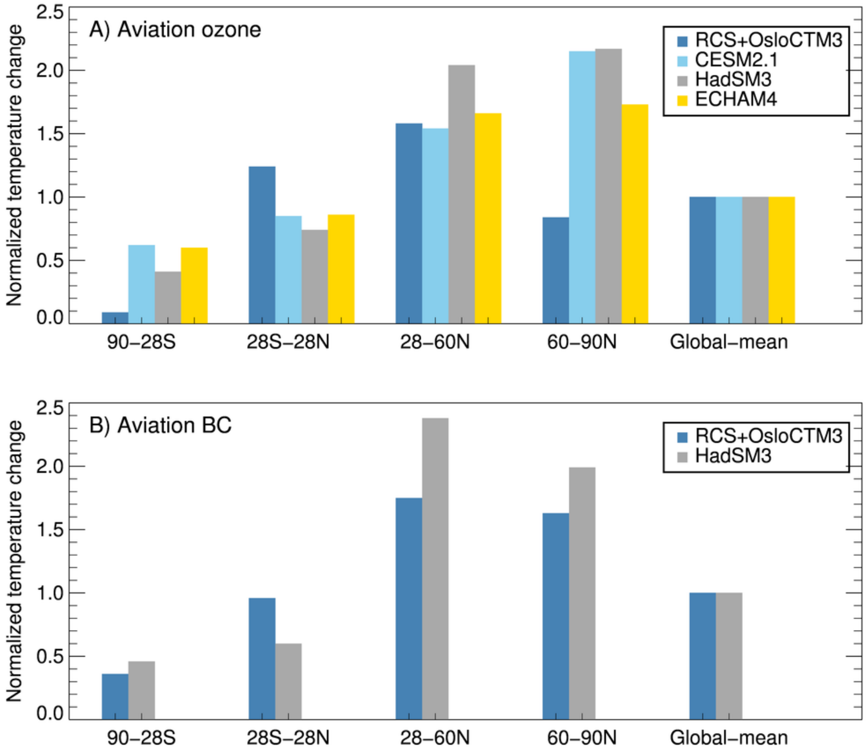


Figure 4: A) Comparison of the regional pattern of surface temperature response to a global aviation ozone perturbation as calculated using the regional climate sensitivities (RCS) from GISS with RF derived from OsloCTM3 (i.e., using the ARTP concept) and simulated by HadSM3, ECHAM4 and CESM1.2. Surface temperature response in each latitude band is normalized by the global mean value. B) Same as A), but for BC.

Supporting material for *“Emission metrics for quantifying regional climate impacts of aviation”*

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Table SI 1: Global and regional aviation emissions used in this study. Emissions are for year 2006 and from the AEDT inventory (Wilkerson et al., 2010). Also included is the accumulated flight distance in each region.

Source Region	BC (kg yr^{-1})	NOx (kgN yr^{-1})	OC (kg yr^{-1})	SO2 (kg yr^{-1})	CO2 (kg yr^{-1})	Flight distance (km)
Global	5.9E+06	8.1E+08	6.4E+06	2.3E+08	5.9E+11	6.7E+10
SAF	4.0E+05	5.6E+07	3.6E+05	1.4E+07	3.8E+10	2.5E+09
NAM	2.2E+06	2.9E+08	2.0E+06	8.2E+07	2.2E+11	1.8E+10
EAS	9.8E+05	1.6E+08	1.1E+06	3.8E+07	1.0E+11	4.6E+09
EUR	1.5E+06	2.2E+08	2.1E+06	5.8E+07	1.5E+11	8.9E+09
SPO	4.6E+05	7.1E+07	4.8E+05	1.8E+07	4.6E+10	2.4E+09
SAS	2.5E+05	4.1E+07	2.3E+05	9.5E+06	2.5E+10	1.6E+09

Table SI 2: Radiative forcing (Wm^{-2}) by component, source region and latitude band for input to the emission metric calculations.

Component	Source region	Radiative forcing (Wm^{-2})				
		Global	90°S-28°S	28°S-28°N	28°N-60°N	60°N-90°N
Contrail-Cirrus	Global	4.6E-02	1.8E-03	2.8E-02	1.6E-01	2.1E-02
	SAF	3.5E-03	4.7E-04	6.5E-03	9.7E-05	9.0E-10
	NAM	1.8E-02	-1.5E-10	7.8E-03	7.5E-02	5.5E-03
	EAS	4.2E-03	-4.8E-10	4.3E-03	1.0E-02	1.2E-03
	EUR	9.5E-03	2.0E-10	1.2E-04	4.9E-02	7.0E-03
	SPO	2.7E-03	7.3E-04	4.9E-03	-1.0E-06	2.5E-11
	SAS	1.6E-03	-2.0E-10	3.0E-03	6.1E-04	9.3E-09
NOx-ozone	Global	1.9E-02	4.8E-03	2.0E-02	3.6E-02	2.3E-02
	SAF	2.0E-03	1.4E-03	2.9E-03	1.0E-03	2.5E-04
	NAM	5.3E-03	7.0E-05	4.0E-03	1.4E-02	8.4E-03
	EAS	4.0E-03	3.6E-04	4.8E-03	6.9E-03	3.8E-03
	EUR	3.0E-03	4.7E-05	1.3E-03	9.0E-03	8.2E-03
	SPO	3.1E-03	2.5E-03	4.8E-03	7.8E-04	-5.1E-05

	SAS	1.6E-03	7.0E-05	2.2E-03	2.4E-03	6.6E-04
BC	Global	5.7E-04	9.7E-05	5.2E-04	1.3E-03	6.6E-04
	SAF	5.4E-05	2.8E-05	8.2E-05	2.6E-05	9.9E-06
	NAM	1.9E-04	1.8E-06	1.3E-04	5.9E-04	2.7E-04
	EAS	1.0E-04	9.0E-06	1.1E-04	2.0E-04	1.0E-04
	EUR	1.1E-04	1.4E-06	4.7E-05	4.0E-04	2.2E-04
	SPO	5.6E-05	4.9E-05	8.5E-05	1.3E-05	7.3E-06
	SAS	5.0E-05	3.8E-06	6.4E-05	7.7E-05	3.3E-05
OC	Global	-4.6E-05	-4.7E-06	-4.9E-05	-9.9E-05	-2.1E-05
	SAF	-4.4E-06	-1.4E-06	-7.3E-06	-1.6E-06	-2.5E-07
	NAM	-1.5E-05	-6.4E-08	-1.3E-05	-4.1E-05	-7.8E-06
	EAS	-7.7E-06	-4.0E-07	-1.0E-05	-1.2E-05	-2.9E-06
	EUR	-1.0E-05	-5.3E-08	-5.3E-06	-3.8E-05	-8.8E-06
	SPO	-5.1E-06	-2.5E-06	-8.5E-06	-8.7E-07	-2.1E-07
	SAS	-3.6E-06	-1.4E-07	-5.4E-06	-4.2E-06	-8.3E-07
Sulfate	Global	-3.2E-03	-2.2E-04	-3.5E-03	-6.5E-03	-2.0E-03
	SAF	-3.0E-04	-9.9E-05	-5.0E-04	-1.1E-04	-1.8E-05
	NAM	-1.1E-03	3.6E-06	-1.0E-03	-3.0E-03	-8.5E-04
	EAS	-5.8E-04	-3.2E-06	-7.5E-04	-9.7E-04	-2.7E-04
	EUR	-5.5E-04	1.0E-06	-2.9E-04	-1.9E-03	-7.8E-04
	SPO	-3.3E-04	-1.1E-04	-5.8E-04	-4.1E-05	7.2E-06
	SAS	-2.7E-04	-2.9E-06	-3.8E-04	-3.5E-04	-7.8E-05
NOx-nitrate	Global	-3.2E-04	-5.6E-07	-2.8E-04	-9.7E-04	-4.1E-05
	SAF	-1.2E-05	-1.9E-07	-1.7E-05	-1.9E-05	-4.8E-08
	NAM	-9.4E-05	5.8E-10	-8.0E-05	-2.8E-04	-1.3E-05
	EAS	-3.2E-05	6.0E-09	-2.4E-05	-1.1E-04	-6.1E-06
	EUR	-1.1E-04	-3.9E-09	-6.7E-05	-4.2E-04	-1.9E-05
	SPO	-5.9E-06	-3.5E-07	-8.3E-06	-8.5E-06	-1.8E-08
	SAS	-4.1E-05	1.7E-09	-5.7E-05	-6.4E-05	-3.2E-07
NOx-methane	Global	-9.3E-03	-6.8E-03	-1.1E-02	-8.6E-03	-6.1E-03
	SAF	-1.1E-03	-8.3E-04	-1.4E-03	-1.0E-03	-7.4E-04
	NAM	-2.7E-03	-2.0E-03	-3.3E-03	-2.5E-03	-1.8E-03
	EAS	-1.7E-03	-1.2E-03	-2.0E-03	-1.5E-03	-1.1E-03
	EUR	-1.5E-03	-1.1E-03	-1.8E-03	-1.4E-03	-9.7E-04
	SPO	-1.4E-03	-9.0E-04	-1.5E-03	-1.1E-03	-8.1E-04
	SAS	-7.0E-04	-4.5E-04	-7.4E-04	-5.6E-04	-4.0E-04

Table SI 3: Regional climate sensitivities (RCS) used in the emission metric calculations [K (W m^{-2})$^{-1}$] (Shindell & Faluvegi, 2009).

Sulfate, OC, nitrate, methane, contrail-cirrus		Forcing region			
		90°S-28°S	28°S-28°N	28°N-60°N	60°N-90°N
Response region	90° S-28° S	0.19	0.05	0.02	0
	28° S-28° N	0.09	0.24	0.1	0.02
	28° N-60° N	0.07	0.17	0.24	0.06
	60° N-90° N	0.06	0.16	0.17	0.31
NOx-induced ozone change		Forcing region			
		90°S-28°S	28°S-28°N	28°N-60°N	60°N-90°N
Response region	90° S-28° S	0.19	0.13	-0.06	-0.03
	28° S-28° N	0.09	0.26	0.09	0.02
	28° N-60° N	0.07	0.15	0.2	0.06
	60° N-90° N	0.06	0.13	0.05	0.07
BC		Forcing region			
		90°S-28°S	28°S-28°N	28°N-60°N	60°N-90°N
Response region	90° S-28° S	0.19	0.06	0.02	0
	28° S-28° N	0.09	0.17	0.07	0.02
	28° N-60° N	0.07	0.24	0.14	0.08
	60° N-90° N	0.06	0.31	0.15	-0.08

Table SI 4 Relative uncertainties adopted in the Monte Carlo analysis.

	Relative uncertainty (1 SD)	Source
BC	39%	AeroCom multi-model mean (Myhre et al., 2013a)
SO$_2$ (sulfate)	34%	AeroCom multi-model mean (Myhre et al. 2013a)
OC	33%	AeroCom multi-model mean (Myhre et al. 2013a)
NOx (nitrate)	50%	AeroCom multi-model mean (Myhre et al. 2013a)
NOx	73%	IPCC AR5, WG1 Ch.8 SM (Myhre et al., 2013b)
CO2	6%	IPCC AR5, WG1 Ch.8 SM (Myhre et al. 2013b)

Table SI ~~3~~5: Global and regional GWP and GTP for time horizons 20 and 100 years of contrail-cirrus, calculated per km accumulated distance. The GTPs are calculated using the impulse response function by Boucher and Reddy (2008) and values are given relative to CO_2 using CO_2 parameters from Joos et al. (2013).

		GWP		GTP	
Component	Source region	H=20	H=100	H=20	H=100
Contrail-cirrus	Global	27	7.5	8	1.1
	SAF	55	15	17	2.2
	NAM	41	11	12	1.6
	EAS	36	10	11	1.4
	EUR	42	11	13	1.6
	SPO	44	12	13	1.7
	SAS	40	11	12	1.6

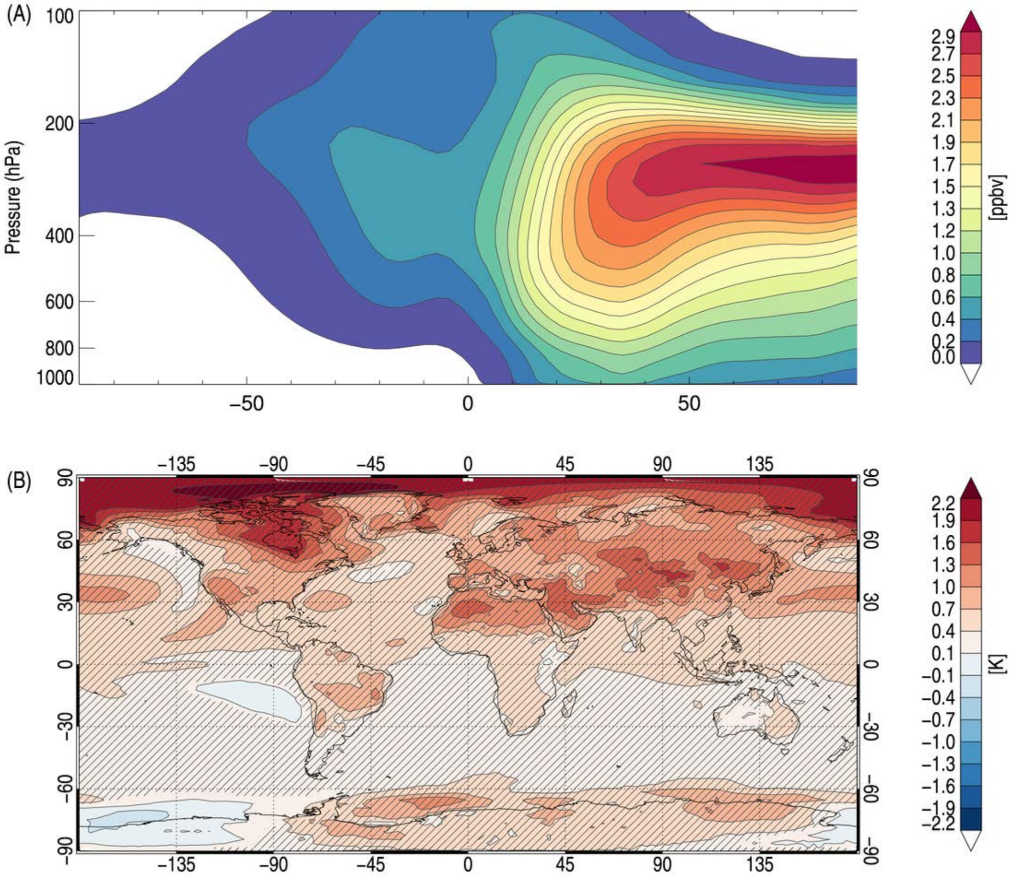
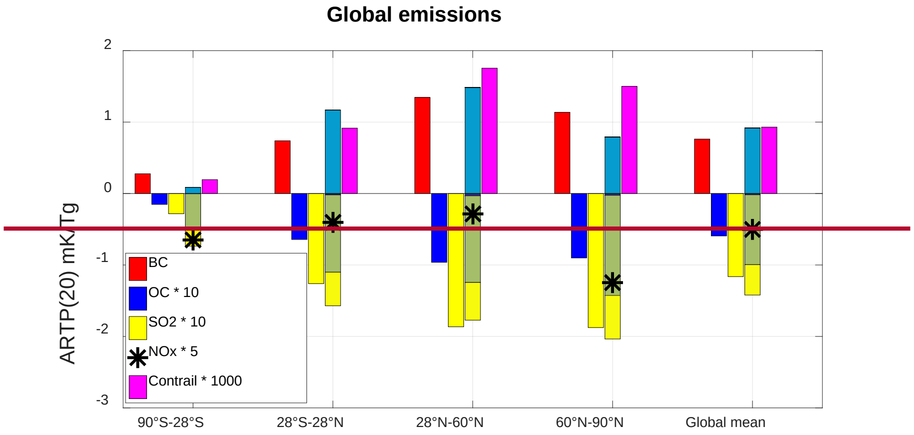


Figure SI 1: (A) Annual mean ~~global aviation induced~~ ozone concentration change from OsloCTM3 caused by global aviation NOx emissions~~from OsloCTM3~~ and (B) annual mean surface temperature response to the aviation ozone perturbation (scaled by a factor 40) as simulated by ~~from~~ CESM1.2. Hatching indicates statistical significance at the 0.05 level.



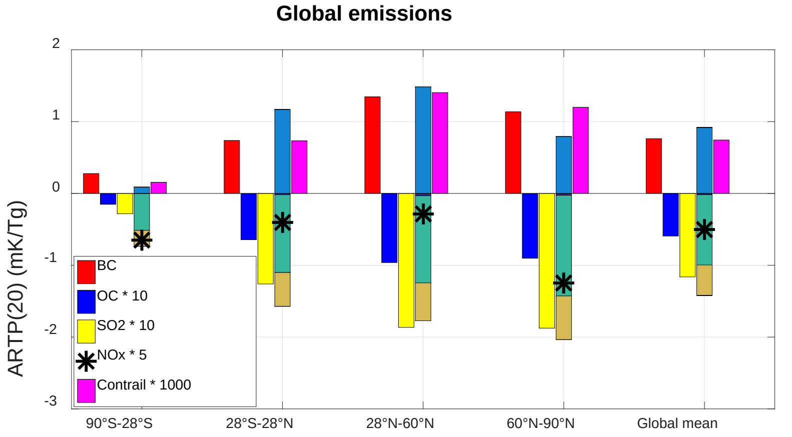
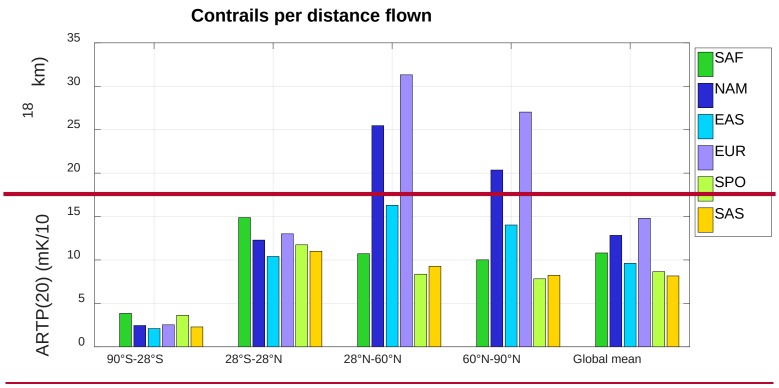


Figure SI 2: ARTP(20) for BC, OC, SO_2, NOx and contrail-cirrus for global aviation emissions. The NOx ARTP(20) is comprised of contributions from ozone (light blue), methane (teal green), ~~and~~ methane-induced ozone (dark yellow) changes and nitrate aerosols (dark blue). The asterisk indicate the net NOx effect.



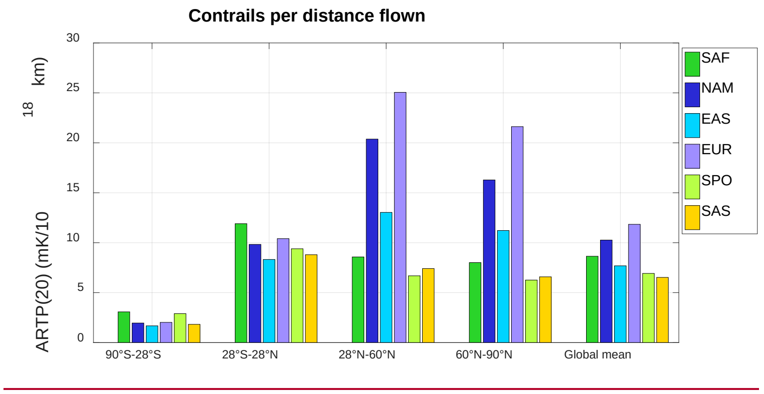


Figure SI 3: ARTP(20) of aviation-induced contrail-cirrus calculated per accumulated km distance.

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