

Reply to referees of the article “An inconsistency in aviation emissions between CMIP5 and CMIP6 and the implications for short-lived species and their radiative forcing”

We thank the two anonymous referees for their comprehensive reviews. In the following, we comment on each of the raised points. Our answers are marked in italics.

Anonymous referee 1

In this study, the authors reveal an “inconsistency” in aviation emissions of the CMIP6 dataset. They then use the EMAC climate model to quantify the impact on simulated ozone radiative forcing and methane lifetime. That impact is small but, at a few percent, not negligible. The impact on aviation aerosol radiative forcing does not meet statistical significance criteria.

The study is short and to the point. It is well written, and the figures and analysis support the discussion well. In my comments, I mostly request clarification of the text in places. However, the aerosol discussion could benefit from being more detailed, and it would be useful to provide guidance on how to interpret past results based on the wrong emissions. For these reasons, I recommend minor revisions.

Main comments:

- Throughout the paper, the authors speak of an “inconsistency”. That is diplomatic of them, but their analysis makes it clear that it is in fact a “mistake”. They provide at least two lines of evidence that the zonal distribution of emissions was not supposed to be like that. Furthermore, I was surprised not to see any mention of the issue on the CEDS github website. There isn’t even a new, corrected version available for download. Why not? There is a CEDS co-author, so they must be aware.
 - *Yes, the CEDS project is aware of this and this issue was flagged a couple months ago on the CEDS GitHub site. See: <https://github.com/JGCRI/CEDS/issues/45>. There has not been a new CEDS data release since this issue was identified, but we have added a work-around noted in the GitHub issue (“for users that would like 100% compatibility with the CMIP5 era data, the CMIP5 3-D aircraft emission data can be scaled to match the global totals in the CEDS data.”). The data will be corrected in the next data release. For now, we would like to maintain the wording “inconsistency” to reflect the larger point made in the conclusions that changes in the spatial distribution of aviation emissions can have noticeable impacts on model results, which calls for improved data that is both up to date and incorporates changes over time.*
- The paper quantifies the impact of the “inconsistency” for the year 2015, finding that it causes the ozone radiative forcing to be about 8% larger. Can that number be used as a rough correction factor for CMIP6-based studies that are already published? How does it vary in time?
 - *It is important to notice that only the ozone RF associated with aviation is 8% larger. The relative impact on the total ozone RF is much smaller. As mentioned in the conclusion, we think that the correction has important implications for studies investigating the aviation climate effect, but is rather not so important for studies investigating climate change on a broader scale.*
 - *The figure of 8 % can probably be used as a rough correction factor, but we recommend using corrected emissions for future studies. The impact of the emission correction*

depends on the treatment of atmospheric dynamics and chemistry in each individual model, and therefore the effect may be smaller or larger than 8 % in any individual model study. The correction factor does not vary in time, except between the historic emissions and future emission scenarios, as described in the introduction of the paper.

- *We have added a paragraph in the conclusions section that explains the expected effects of a different background, as would be expected in future scenarios. We consider a detailed quantification of the dependence of the inconsistency's effect on the background atmospheric chemistry, which could be achieved by performing additional sets of simulations, out of the scope of this paper.*
- The impact on aerosol radiative forcing is discussed in a 5-line paragraph. That feels rushed. Granted, the impact on radiative forcing is affected by the large interannual variability in cloudiness. But can't the authors say something about the impact on aviation aerosol burden or residence time? The northward shift in emissions would certainly affect those.
 - *The black carbon aerosol burden and aerosol number concentration would be lower in a scenario with the CMIP5 latitudinal distribution of emissions. We included a figure in the paper to show this difference and added some corresponding explanations in the text.*

Other comments:

- Line 6: Why single out ozone and leave out the result on methane lifetime?
 - *We added the result on the methane lifetime to the abstract.*
- Line 9: The abstract also lacks a concluding sentence. What are the implications for aviation radiative forcing derived from CMIP6 emissions?
 - *We added a concluding sentence to the abstract.*
- Lines 12-13: I suppose that statement tries to make the point that CMIP6 emissions are used beyond CMIP6. Perhaps then clarify that those studies used CMIP6 emissions despite not contributing to the CMIP6 database itself.
 - *We changed the formulation of the sentence to better express that the mentioned studies make use of the CMIP6 outside of its original purpose.*
- Line 21: "differs by" is vague. I suggest clearly saying that CMIP6 distributions need to be multiplied by the given latitude-dependent factors to fix the problem discussed here. It would also be useful to elaborate on the coefficients. I suppose the 1.344 and 1.912 factors are related to the shape of the emission distribution along latitudes. Is it some kind of emission-weighted mean cosine (or cosine squared) of latitude? Finally, it would be useful to repeat here that the correction is time-independent because emission patterns do not vary with time in those datasets.
 - *You are correct that the factors are an emission-weighted mean cosine (squared) of the latitude. We added two sentences to explicitly describe this and how to apply the correction.*
- Lines 29-30: I suggest spelling out the implication that CMIP6 emissions for those species also need correcting for the same factors as above.
 - *We have also formulated this more explicitly in the sentences mentioned in the previous comment.*
- Lines 34-35: Could cite Bock and Burkhardt (2019), for example, <https://doi.org/10.5194/acp-19-8163-2019> in support of that statement.
 - *We added the citation.*
- Line 70: But again using emission data for 2015?
 - *Yes, we clarified this in the text.*
- Caption of Figure 2: The lines have different styles, but also different colours, which should be mentioned.
 - *We added the colors to the figure caption.*
- I am missing a concluding statement, here. Something saying that the shift in mean emission latitude probably had a small impact on the RF of aviation NO_x emissions, an impact that is often neglected in climate studies. In addition, it would be worth noting that emissions will

probably shift again in the future, and that it would be good to have emission scenarios that allow the study of the climate impacts of that shift.

- *We added a concluding sentence.*

Anonymous referee 2

I have read the paper entitled “An inconsistency in aviation emissions between CMIP5 and CMIP6 and the implications for short-lived species and their radiative forcing” by Thor et al.

It covers unstated differences in the spatial distribution of emissions between the CMIP5 and CMIP6 inventories and the implications for short-lived climate forcing and subsequent impacts.

This paper represents an important novel contribution to the scientific community, and I recommend it for publication in the journal Geoscientific Model Development.

The paper is well-written, and the methods and results are well-described. As such, I have no major comments, but please find a few specific comments below.

General comments:

The biggest question that I have is why these emissions inventories are different in the first place. Is there a likely calculation error performed by the emissions inventory community that would have led to this inconsistency? If there is a methodological error, it might be important to highlight some of the conversions that could have caused this inconsistency.

- *This error occurred due to an incorrect summation of vertical emissions when generating the normalized spatial proxy. As mentioned above, this has been corrected and the corrected data will be included in the next CEDS data release. We are not able to investigate the reason why the future emission data differs, but a workaround has been noted here: (<https://github.com/JGCRI/CEDS/issues/45>.) We have added a paragraph at the very end of the paper that mentions this and reflects the current status of investigations.*

In addition, also show if this inconsistency changes with the CMIP emissions year.

- *We added a sentence to indicate that the inconsistency, just like the geographical distribution of emissions themselves, is constant over time*

Importantly, if the inventory is different for aviation, there might be other sectors for which the same distributional inconsistency exists.

- *The reported inconsistency is likely related to the specific processing required for international aviation emissions, whereas for other sectors emissions are reported and processed on national levels. We could not find any similar inconsistency in other sectors.*

A comment on what might have caused this inconsistency, and a comment in the conclusion of this paper indicating whether this inconsistency is found for other sectors would greatly help the scientific community to fix these types of differences in future inventories.

The paper shows that the difference is the largest for polar emissions (page 2, line 24). As a result, an additional difference in radiative impact may occur due to differences in the impact of black carbon on ice pack darkening. Since this is not mentioned, I assume it is not included in this study. If it is evaluated, please comment on it, or if not, please include a comment.

- *The set of aerosol simulations contain black carbon scavenging and the resulting albedo changes, but these outputs were not saved. The QCTM have identical aerosol representations and are therefore not affected. Therefore, we are unfortunately unable to quantify the ice pack darkening or the RF caused by this effect. We have added a figure to show the difference in aviation-induced black carbon concentration changes between the two emission inventories and some additional discussion in the text.*

Line-by-line

Line 34-35: The impact on contrails might be substantial too and it would be good to mention the differences could be significant. For support consider referencing:

- Bock, L., & Burkhardt, U. (2019). Contrail cirrus radiative forcing for future air traffic. *Chem. Phys*, 19(12), 8163–8174. <https://doi.org/10.5194/acp-19-8163-2019>
- Lund, M. T., Aamaas, B., Berntsen, T. K., Bock, L., Burkhardt, U., Fuglestedt, J. S., & Shine, K. P. (2017). Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics*, 8(3), 547–563. <https://doi.org/10.5194/esd-8-547-2017>
 - *The contribution of aircraft soot emissions to contrail RF is indeed a factor that we have not considered, but would contribute a small amount to the total RF difference caused by*

the inconsistency. We added a paragraph at the end of the results section where we qualitatively describe the expected effect. A more detailed analysis would be interesting, but as contrail formation was not investigated in the simulations performed for this study, we consider a more detailed quantification out of the scope of this manuscript.

Methods section [Page 2 & 3]: This section describes the coupled climate chemistry model (line 39 to 49), but in the next paragraph it seems that the model is run with fixed meteorology using “quasi-chemical transport model” in the case of ozone, and for aerosols, “nudged meteorology ... using reanalysis data”. The methods section would be easier to follow by clarifying this earlier in the methods section, perhaps by stating earlier in the methods section how this model is applied (e.g. in line 41) before the description of the model continues.

- *We added a summarizing paragraph to the beginning of the methods section which hopefully clarifies the differences between the two sets of simulations.*

Conclusion: I find this paper could elaborate on potential other implications of this difference in emissions distribution. For instance, would we also expect a difference in air quality impacts due to these differences?

- *We added a paragraph at the end of the results section on the effect of the inconsistency on two indicators for air quality, the surface ozone mixing ratio and the surface nitrogen oxide mixing ratio. We conclude that the effect of the inconsistency on air quality is small.*

An inconsistency in aviation emissions between CMIP5 and CMIP6 and the implications for short-lived species and their radiative forcing

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Abstract. We report on an inconsistency in the latitudinal distribution of aviation emissions between the data products of phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP). Emissions in the CMIP6 data occur at higher latitudes than in the CMIP5 data for all scenarios, years, and emitted species. A comparative simulation with the chemistry-climate model EMAC reveals that the difference in nitrogen oxides emission distribution leads to reduced overall ozone changes due to aviation in the CMIP6 scenarios, because in those scenarios the distribution of emissions is partly shifted towards the chemically less active higher latitudes. The radiative forcing associated with aviation ozone is 7.6% higher and the decrease of methane lifetime is 5.7% larger for the year 2015 when using the CMIP5 latitudinal distribution of emissions compared to when using the CMIP6 distribution. We do not find a statistically significant difference in the radiative forcing associated with aviation aerosol emissions. In total, future studies investigating the effects of aviation emissions on ozone on climate should consider the inconsistency reported here.

1 Introduction

Emission data are a key contribution to the Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring et al., 2016). This framework provides both, historical emissions (Hoesly et al., 2018) and emissions for future scenarios (Riahi et al., 2017; Gidden et al., 2019). ~~Several studies have~~ Apart from their usage within the CMIP itself, several studies have also used the aviation emissions provided within the framework of CMIP6 ~~(e.g., Quadros et al., 2020; Righi et al., 2021)~~ for other purposes, as they present an available dataset with future projections that are consistent with those of other sectors (e.g., Righi et al., 2021). The geographical and annual distribution of aviation emissions are identical throughout all historical and scenario data sets in CMIP6, leaving only the total annual emission amounts as variables that are different for each year and each scenario. According to the documentation (Hoesly et al., 2018), the geographical distribution of the CMIP6 aviation emissions is based on that of the CMIP5 aviation emissions (Lamarque et al., 2010), which in turn are derived from the Future Aviation Scenario Tool (FAST, Lee et al., 2005) for the European QUANTIFY project (Hoor et al., 2009), and is not affected by the regridding

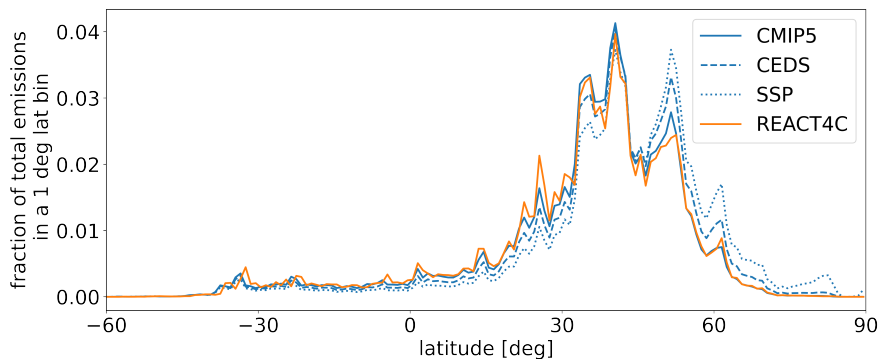


Figure 1. Fraction of total aviation emissions as a function of latitude. The solid blue line is based on the RCP 4.5 scenario for the year 2000 (CMIP5, Lamarque et al., 2010). The dashed blue line is based on historical emissions provided in the CEDS (CMIP6, Hoesly et al., 2018). The dotted blue line is based on the SSP2 4.5 scenario for the year 2015 (CMIP6, Fricko et al., 2017; Gidden et al., 2019). The orange line is based on the REACT4C inventory (Søvde et al., 2014).

performed within CMIP6 (Feng et al., 2020). Based on this information we would expect an identical geographical distribution of the aviation emissions in CMIP5 and CMIP6.

Here, we report on an inconsistency in the spatial pattern of aviation emissions between CMIP5 (Lamarque et al., 2010) and CMIP6 (Gidden et al., 2019; Feng et al., 2020). The latitudinal emission distribution differs by an approximate factor of $1.344 \cos \phi$ for historic emissions provided in the Community Emissions Data System (CEDS, Hoesly et al., 2018) and by an approximate factor of $1.912 \cos^2 \phi$ for the Shared Socioeconomic Pathways (SSP) scenarios (Gidden et al., 2019), where ϕ is the latitude (Fig. 1). This difference is particularly noticeable in the North Polar region, where emissions are several times larger in the CMIP6 data sets, but in terms of total amount of emissions, the difference is largest in the regions from $\sim 50^\circ\text{N}$ to $\sim 65^\circ\text{N}$ and from $\sim 25^\circ\text{N}$ to $\sim 40^\circ\text{N}$, where most emissions occur (see also Fig. 2). A comparison with an independent aviation emission inventory derived in the REACT4C project (Søvde et al., 2014) gives a very good match with the CMIP5 data set. The difference is observed for aviation emissions of nitrogen oxides (NO_x), black carbon (BC), and CO_2 . Other emitted species (CO, NH_3 , NMVOC, SO_2 , organic carbon) have an identical geographic distribution to that of NO_x and BC in CMIP6, but were not provided in the CMIP5 data. The factors by which the latitudinal emission distributions differ are independent of the year, as the geographical pattern of emissions is also constant over time in CMIP6. To obtain a aviation emissions that have the same total amount of emissions as in CMIP6, but exhibit approximately the same latitudinal distribution of emissions as the CMIP5 emissions, one has to multiply the CMIP6 CEDS historic emissions (until the year 2014) of all species by $1.344 \cos \phi$ and the CMIP6 SSP scenario emissions (from the year 2015) of all species by $1.912 \cos^2 \phi$. The parameters 1.344 and 1.912 originate from the latitudinal distribution of aviation emissions and ensure that the total amount of emissions is not modified.

The aim of this paper is to investigate the impacts of the differences in the latitudinal distribution of emissions on aviation-induced ozone and aerosols and on their radiative forcing (RF). We do not consider emissions of CO_2 , as it is a well-mixed

greenhouse gas with a long lifetime, implying that the spatial distribution of the emissions has a minor effect on the CO₂-induced climate effect. We also do not consider the potential differences in the contrail climate effect, because the CMIP data do not contain data on flight distance per area, which would be required for their computation ([Bock and Burkhardt, 2019](#)).

45 In Section 2, we introduce the used earth system model and simulation set-up and in Section 3, we present results on the aviation-induced atmospheric ozone concentration and aerosol distributions and differences in radiative fluxes.

2 Method

To investigate the effect of the difference in latitudinal distribution of aviation emissions on ozone, aerosols, and the related radiative forcings, we perform simulations with the chemistry-climate model ECHAM/MESSy Atmospheric Chemistry (EMAC),
50 using each of the geographical distributions, but identical total amounts of emissions. [For the investigation of aviation-induced ozone changes, we perform a set of 5-year simulations, where the model is configured as a quasi-chemical transport model \(QCTM\) and uses a source apportionment \(tagging\) method. For the investigation of the aviation-induced aerosol effect, we perform a separate set of 13-year simulations, where the model is configured as a chemistry-climate model with nudged meteorology.](#)

55 The EMAC model is a numerical chemistry and climate simulation system that includes sub-models describing tropospheric and middle atmosphere processes and their interaction with oceans, land and human influences (Jöckel et al., 2010). It uses the second version of the Modular Earth Submodel System (MESSy2) to link multi-institutional computer codes. The core atmospheric model is the 5th generation European Centre Hamburg general circulation model (ECHAM5, Roeckner et al., 2006). The physics subroutines of the original ECHAM code have been modularized and reimplemented as MESSy sub-models
60 and have been continuously been further developed. Only the spectral transform dynamical core, the flux-form semi-Lagrangian large scale advection scheme, and the nudging routines for Newtonian relaxation are remaining from ECHAM.

For the simulations of aviation-induced ozone changes in the present study, we applied EMAC (MESSy version 2.54.0.3) in the T42L90MA-resolution, i.e. with a spherical truncation of T42 (corresponding to a quadratic Gaussian grid of approx. 2.8 by 2.8 degrees in latitude and longitude) with 90 vertical hybrid pressure levels up to 0.01 hPa. The applied model setup
65 comprised RF calculations based on the sub-model RAD (Dietmüller et al., 2016) and the sub-model TAGGING (version 1.1, Grewe et al., 2017; Rieger et al., 2018) for the attribution of RF to emissions from the aviation sector (Mertens et al., 2018). The simulations use specified dynamics and the set-up is very similar to the one of the simulation RC1SD-base-10a described in detail by Jöckel et al. (2016)([see also Mertens et al., 2022b](#)). [The gas phase mechanism is implemented using the sub-model Module Efficiently Calculating the Chemistry of the Atmosphere \(MECCA, Sander et al., 2011\) and incorporates the chemistry of ozone, methane and odd nitrogen. Alkanes and alkenes are considered up to C₄, while the oxidation of C₅H₈ and some non-methane hydrocarbons \(NMHCs\) are described with the Mainz Isopren Mechanism version 1 \(von Kuhlmann et al., 2004\). Further, heterogeneous reactions in the stratosphere \(sub-model MSBM, Jöckel et al., 2010\) as well as aqueous phase chemistry and scavenging \(SCAV, Tost et al., 2006\) are included. Emissions of methane \(CH₄\) are not considered explicitly. Instead, CH₄ mixing ratios are relaxed towards observations using Newtonian relaxation with the](#)

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75 [sub-model TNUDGE \(Kerkweg et al., 2006\)](#). Using the sub-model LNOX, Lightning NO_x is parameterised after [Grewe et al. \(2002\)](#) with global total emissions of $\sim 4.5 \text{ Tg(N) a}^{-1}$, which is within the range given by [Schumann and Huntrieser \(2007\)](#). Emissions of NO_x from soil and biogenic C₅H₈ emissions were calculated using the MESSy sub-model ONEMIS ([Kerkweg et al., 2006](#)) using parameterisations based on [Yienger and Levy \(1995\)](#) for soil-NO_x and [Guenther et al. \(1995\)](#) for biogenic C₅H₈.

For one simulation we use the unaltered CMIP6 aviation emissions of the SSP2 4.5 scenario ([Fricko et al., 2017](#)) for the 80 year 2015, whereas for a second simulation we use the CMIP6 aviation emissions with their latitudinal distribution changed to be equal to that of the CMIP5 emissions. Other simulation settings are identical. The presented results are obtained as a 5-year mean after a spin-up period of 6 months in ~~quasi-chemical transport model (QCTM)~~ QCTM mode ([Deckert et al., 2011](#)), where feedback between chemistry and dynamics is suppressed, and using meteorology data reaching from 2013 to 2017 and specified dynamics by Newtonian relaxation towards ECMWF ERA-Interim reanalysis data ([Dee et al., 2011](#)). For 85 the spin-up period, we use meteorology data from the second half of 2012. The simulations were initialized from a previous 1.5-year simulation including TAGGING for the spin-up of the TAGGING tracers. This spin-up simulation itself was initialized from the long-term (since 1950) SC1SD-base-01 simulation which is similar to the RC1SD-base-10a simulation ([Jöckel et al., 2016](#)).

For the simulations of the aviation-induced aerosol effect, we used EMAC with the aerosol ~~submodel~~ [sub-model](#) MADE3 90 (Modular Aerosol Dynamics model for Europe, adapted for global applications, third generation; [Kaiser et al., 2014, 2019](#)) in the configuration described by ~~Righi et al. (2020)~~ [Righi et al. \(2020, 2023\)](#). With respect to the version adopted for the ozone changes, the EMAC-MADE3 setup for aerosol uses a lower vertical resolution with 41 layers, mostly covering the troposphere and the lower stratosphere, and a simplified chemistry scheme, only including the reactions relevant for the aerosol processes. The aerosol simulations cover a period of 13 years ~~, from 2006 to 2018,~~ with nudged meteorology using the ECMWF ERA- 95 Interim reanalysis data ~~, from 2006 to 2018,~~ and again using emissions for the year 2015. The QCTM mode and the tagging method cannot be applied for investigating the aerosol effects, due to the role of the cloud feedback and the complexity of the liquid-phase chemistry for sulfate, respectively. Hence, the statistical significance of the changes in the aerosol RF between the original and the corrected emission dataset is evaluated using a paired sample *t* test at the 95% confidence level.

3 Results

100 Our analysis for the SSP scenarios shows that regional emission amounts from aviation differ substantially in the northern mid-latitudes (Fig. 2). Emissions of NO_x north of 45°N are 36.8% lower and emissions south of 45°N are 31.9% higher when using the CMIP5 latitudinal distribution of emissions compared to when using the unaltered CMIP6 emissions. The mean emission latitude shifts from 41.3°N for the CMIP6 latitudinal distribution to 34.3°N for the CMIP5 latitudinal distribution.

The difference in the ozone distribution between the two QCTM simulations reflects the latitudinal difference in aviation 105 emissions (dashed and solid lines in Fig. 2, respectively). However, atmospheric dynamics and the larger chemical activity in tropical latitudes lead to a southward shift of the ozone burden difference with respect to the emission difference. The increased NO_x emissions southwards of 45°N cause a positive ozone burden whose value (2.13 Tg) is larger than the absolute value of

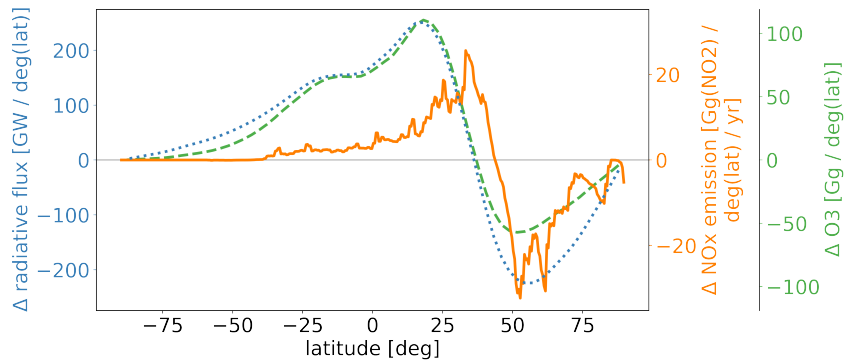


Figure 2. Differences (CMIP5 - CMIP6) of NO_x emissions (solid orange line), O_3 burden (dashed green line), and radiative flux (dotted blue line) from two simulations with identical total amount of aviation emissions, but different latitudinal distributions, as a function of latitude.

the negative ozone burden caused by the decreased NO_x emissions northwards of 45°N (-1.18 Tg). In total, using the CMIP5 latitudinal pattern of emissions increases the atmospheric ozone burden by 0.95 Tg , corresponding to an increase of 3.4% in the total ozone burden attributed to aviation.

We also compute the stratospherically adjusted radiative flux at the tropopause resulting from these differences in the ozone concentration distribution. The pattern of the radiative flux difference between the two simulations closely follows the pattern of the ozone burden difference, but the radiative flux decrease at high northern latitudes is more pronounced than the corresponding ozone decrease (Fig. 2). We show radiative flux instead of radiative forcing to keep all quantities in Fig. 2 independent of the area for better comparability. The radiative forcing attributed to aviation emissions is 30.82 mW m^{-2} in the simulation with unaltered CMIP6 emissions and 33.16 mW m^{-2} in the simulation using the CMIP5 emission pattern, corresponding to a difference of 2.34 mW m^{-2} or 7.6%. The difference in total RF between the two simulations is 2.08 mW m^{-2} . The total difference is smaller due to the non-linearity between nitrogen oxide emissions and ozone changes. Emissions from other sectors cause weaker radiative effects in a more polluted atmosphere, partly compensating for a larger aviation RF.

Transport emissions also influence the lifetime of methane, with aviation emissions generally leading to a lifetime decrease (Mertens et al., 2022b)(Mertens et al., 2022a). In the simulation using the CMIP5 emission pattern, we found a 5.7% larger decrease of lifetime for aviation. All these changes are statistically significant because they are 5 to 6 times larger than their standard deviation over the 5-year simulation period. For context, aviation emissions have consistently increased over time, with a decadal increase ranging from 10-25%, depending on the time period (O'Rourke et al., 2021). This points to the importance of accurately quantifying not only the magnitude and spatial distribution of aviation emissions, but their changes over time.

~~We also investigate the difference in aerosol RF between the two simulations, but cannot detect a significant difference. For the simulations with the~~

Finally, we investigate the impact of the corrected emissions on aviation-induced changes in aerosol concentrations. This is shown in Fig. 3 for BC and reveals that adopting the CMIP5 and latitudinal distribution of emissions results in a lower

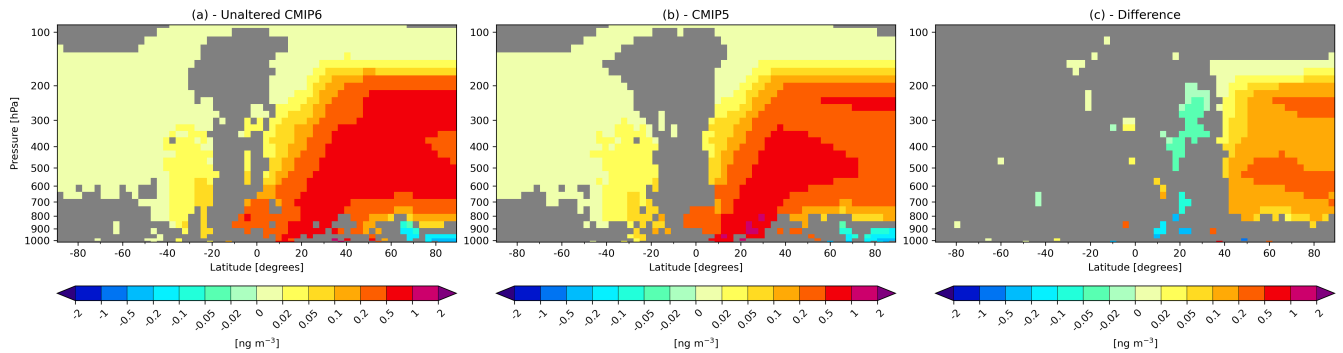


Figure 3. Zonally averaged aviation-induced changes in black carbon concentration simulated by the model using the unaltered CMIP6 (a) and CMIP5 (b) inventory, and their difference (c). Gray areas mark non-significant changes at the 95% confidence level.

130 aviation-induced BC concentration compared to the unaltered CMIP6 emissions inventory. Differences around $0.1\text{--}0.2\text{ ng m}^{-3}$ are found throughout the troposphere at high latitudes ($> 40^\circ\text{N}$). Even larger differences, up to 0.5 ng m^{-3} , can be seen at and below the typical cruise altitude ($\sim 200\text{--}300\text{ hPa}$). Analogous differences are found for aviation-induced aerosol number concentration (not shown). These changes can be relevant for the quantification of the impacts of aviation aerosol on climate, through their interactions with both warm clouds and cirrus (e.g., Gettelman et al., 2013; Righi et al., 2021) as well as ice surface albedo (Kang et al., 2020). The large variability of the climate system associated with aerosol-cloud interactions, however, hampers a robust quantification of the aerosol RF from aviation. Here, we quantify a RF of -46.0 mW m^{-2} and -54.7 mW m^{-2} , respectively, i.e. a difference of for the simulations with the CMIP5 and unaltered CMIP6 emissions, respectively. This means that the climate impact of aviation due to aerosol is reduced (in absolute terms) by 8.7 mW m^{-2} (15.9%), but with a low statistical significance of, i.e. 16%. This reduction is consistent with the aforementioned differences in aviation-induced particle concentrations, but its statistical significance is low (79.8%. This is related to the large variability associated with aerosol RF compared to those associated with ozone RF, especially) for the reasons outlined above.

The effect of the difference in emissions on air quality is small. For example, the differences in the surface mixing ratio of ozone and nitrogen oxides between the two QCTM simulations are smaller than 0.5 % and 2.1 % at all locations, respectively. For nitrogen oxides, 98 % of the 2.8 by 2.8 degree grid cells in the model exhibit differences smaller than 0.2 %.

145 In this study, we are not considering the effect that a different latitudinal distribution of aviation soot emissions would have on contrail RF. According to Bock and Burkhardt (2019), a 50% reduction in soot emissions could lead to a 14% reduction in contrail RF. This implies a lower contrail RF north of 45°N and a higher contrail RF south of 45°N when using the CMIP5 latitudinal distribution of emissions compared to when using the unaltered CMIP6 emissions. The net effect may be a lower contrail RF due to the rarer occurrence of persistent contrails in tropical areas, but this effect is likely small due to the role of aerosol-cloud interactions (see, e.g., Righi et al., 2013) relatively small effect of soot emissions on contrail RF.

4 Conclusions

In summary, the inconsistency in the latitudinal distribution of aviation emissions between CMIP5 and CMIP6 leads to differences not only in the latitudinal distributions and regional emission amounts, but also in the total amounts of resulting ozone changes, methane lifetime changes, and RF attributed to aviation. The usage of the CMIP6 latitudinal distribution of emissions leads to an overall lower climate effect of aviation emissions, even though the same total global amount of emissions was assumed in the simulations. The difference of 2.34 mW m^{-2} reported in this study for the SSP2 4.5 scenario is small in the context of anthropogenic climate change, but constitutes 7.6% of the RF attributed to aviation ozone in our model. We therefore recommend that scholars studying the effects of aviation emissions on ozone and climate consider the inconsistency in the latitudinal distribution of aviation emissions reported here. We also investigated the effect of the inconsistency on aerosol RF, but could not detect a significant difference.

The impact of the inconsistency in the latitudinal distribution of aviation emissions on the RF and climate also depends on the background chemical composition of the atmosphere, which is a function of future global emission and pollution pathways. In a warmer and more polluted atmosphere, the chemical activity would be generally larger, particularly at high latitudes (Skowron et al., 2021). Therefore, the negative ozone burden change at Northern mid and high latitudes would likely be closer to the positive change at tropical and southern latitudes, leading to a smaller net relative effect of the inconsistency in terms of ozone burden and RF. The opposite would be expected for a less polluted atmosphere.

Furthermore, the results emphasize the importance of a correct and realistic geographic distribution of emissions when studying their effects on atmospheric composition and climate. Future aviation emission datasets should also consider temporal changes in the spatial distribution of emissions. No spatial changes over time were incorporated in either the CMIP5 or CMIP6 aviation datasets because such changes have not been estimated by the research community. The spatial distribution of aviation emissions have certainly changed over time, however (Quadros et al., 2022). For example, from 1990 to 2017 the share of estimated NO_x emissions from flights originating in (roughly) the northern hemisphere (here Former Soviet Union, Europe, China, and North America) declined from 73% to 62%, implying a shift in aviation emissions away from the northern mid-latitudes (O'Rourke et al., 2021). Such shifts in the mean aviation emission latitude in the past and future have an impact on the climate effects of aviation NO_x emissions, which many climate studies neglect.

We note in closing that the difference between CMIP5 and CEDS was found to be caused by an error in data pre-processing in CEDS and will be corrected in the next data release (Smith, 2022). This type of error can occur during conversion between masses and mixing ratios.

Code and data availability. The Modular Earth Submodel System (MESSy) is continuously further developed and applied by a consortium of institutions. The usage of MESSy and access to the source code is licensed to all affiliates of institutions which are members of the MESSy Consortium. Institutions can become a member of the MESSy Consortium by signing the MESSy Memorandum of Understanding. More information can be found on the MESSy Consortium website (<http://www.messy-interface.org>, last access: 10 October 2022). The simulations presented here have been performed with a release of MESSy based on version d2.54.0.3-pre2.55-02. All changes are available

in the official release (version 2.55). The namelist setups used for the simulations and the scripts used for the creation of the figures are given
185 in Thor (2022).

Author contributions. R. N. T. discovered the inconsistency. S. M. and V. G. conceptualized the study. M. M., R. N. T., and M. R. carried out the simulations. M. R., S. B., P. G., and P. J. prepared the modified CMIP6 input emission data for the model simulation to be consistent with the CMIP5 spatial emission pattern. S. B. calculated the methane lifetime. M. R. and J. H. calculated the aerosol RF. R. N. T. created all figures and wrote the manuscript with the help of all co-authors.

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

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