Answer to Reviewer #1:

The article estimates the increase in contrail cirrus radiative forcing (RF) between 2006 and 2050, separating the contributions from the increase in air traffic and cruise altitude, reduction in soot emissions, and background meteorology differences linked to future climate change. The results report an RF increase by a factor of 3 with a relatively modest reduction (15%) from a 50% soot number emissions decrease, concluding that the increase in RF linked to traffic growth (factor of 4) cannot be counterbalanced by improvements in propulsion efficiency and soot emissions.

The manuscript addresses a relevant topic, providing guidance for attribution and mitigation options for the contribution of the aviation sector to climate change. The methodology is sound and based on a tested model and all the sections of the manuscript are clearly presented in a logical way. The manuscript definitely fulfils ACP's standards, and is unreservedly recommended for publication. Only very minor suggestions are made that I hope will improve the clarity and interpretation of the results.

Thank you for your very positive judgement and for comments.

Specific suggestions:

Pg 4 ln 22: It would probably be useful to expand on the magnitude of the future flight altitude shift and add a reference. This will enable the reader to get a sense of the sensitivity of your model to such changes.

This is a very good point but unfortunately the information on the shift that we were able to acquire is limited. We received the data set horizontally gridded and with relatively low vertical resolution (30 levels) from C.-C. Chen, NCAR. We know that the shift causes the maximum of air traffic distance in 2050 to be located at 200 hPa instead of 240 hPa as in the old inventory. Additionally M. Gupta from the FAA assured us that this shift of flight altitude is a realistic consumption in the Volpe future scenario and wrote us that new aircraft seem to fly at higher altitude than the old ones with a difference ranging between 0.3-1.5km. The shift from 200 to 240 hPa lies with about 1 km in the middle of this range.

We added "by between 0.3 and 1.5 kilometres (pers. comm. Mohan Gupta, FAA), resulting in the shift of maximum flight density seen in Fig. 1a" .

Pg 6 ln 19: add a comma after the word "large".

Thanks.

Pg 6 ln 19: It would probably be useful to expand, in the sentence starting in ln 19, if the reduction in ice crystal numbers in the tropics is accounted for in the parameterisation.

The reduction of initial ice crystal numbers is not considered in our parameterization as we describe a constant initial ice crystal concentration for contrail.

We modified for clarification this part: “It needs to be pointed out that contrail optical depth is likely overestimated in the tropics, since in the tropics contrails form within a few degrees of the temperature threshold (Schmidt-Appleman criterion) limiting ice nucleation in the contrail (Bier and Burkhardt, 2019), a process that is not resolved in our simulations (Sect. 2.3). Therefore optical depth and lifetimes of contrails will be overestimated (Burkhardt et al., 2018) and consequently radiative forcing.”

Pg 9 ln 8: remove “of the”

Thanks.

Pg 9 ln 16: add the period in “et al”

Thanks.

<u>Answer to Reviewer #2:</u>

This is a very interesting and generally clearly written paper, in an important area where there have been rather few earlier papers in the literature. I recommend it be accepted following modifications.

The more important comments are preceded by an "M".

Thank you for your in-depth review that helped us to improve our paper.

1:12 It would be useful to say in the abstract what the 2050 forcing is, in W/sq.m, rather than just reporting the 2050:2006 ratio (especially as this paper disagrees significantly with the only other recent study).

Yes, we added the absolute number of the 2050 contrail cirrus radiative forcing.

1:16 The authors may have been up against a word limit here, but I feel it would be useful to qualify the statement on the global-mean insignificance of the climate change by a comment that there are regional forcing differences resulting from the effect of climate change.

Yes, we added this point.

2:19 This crops up a few times in the manuscript. Is it correct that it is "a lower number OF LARGER ice crystals"? If so, I think this would add clarity.

As we wrote here about newly nucleated ice crystals, they may not or only very slightly be larger than when forming more ice crystals. But when deposition starts, then these fewer crystals could grow larger.

We added "with ice crystals grow to larger sizes and sedimentation is initiated earlier in the life cycle.".

2:33 Another frequent (albeit minor) issue. Optical depth is a wavelength-dependent quantity. I presume the authors mean "visible"? This should be clarified.

Yes, we added "visible" in a few locations.

3:9 "different sensitivities" – different sensitivities to what? Changes in air traffic volume?

To clarify this sentence we add: "to an increased air traffic volume".

M4:10 I realise that the authors may push back on this suggestion, but given the likely policy interest in the results from this paper, it may be useful to provide a couple of sentences on how the AEDT scenarios are compliant, or not, with CORSIA ("stabilize CO2 emissions by 2020 and reduce 2005 emissions by 50% by 2050"), given that the CORSIA agreement came after these scenarios were developed. I realise that this is not simple, given the role that offsetting might play in meeting the CORSIA targets. Perhaps there is a catch-all paper on the implications of CORSIA on future emission scenarios in the aviation literature that can be referred to?

This is a very interesting connection.

The AEDT 2050 Baseline describes unconstrained growth with a factor of 4.8 increase in fuel burn relative to the year 2006. The 2050 Scenario1 includes an improvement of fuel efficiency by 2% per year and additional NO_x emission reductions. The CORSIA aims, to stabilize net CO_2 emissions from international civil aviation at 2020 levels and to reduce the net CO_2 emissions to half of what they were in 2005, by 2050, would require a much larger reduction in fuel burn or significant carbon offsetting. It is important to realize that while carbon offsetting may be helpful in order to limit the impact of CO_2 emissions the large impact of contrail cirrus is unaffected by carbon offsetting.

We added: "As fuel burn increases by a factor of 4.8 between 2006 to 2050 Baseline and still by a factor of 2.7 between 2006 and 2050 Scenario 1 (Unger et al., 2013), the specifications of the future projections do not meet the requirements of the international CORSIA agreement unless the remaining necessary CO_2 emission reductions are introduced purely by carbon offsetting.

4:22 – 4:23 What is the vertical resolution of the AEDT dataset? Is the change from 200 to 240 hPa a shift in one level in the dataset (in which case, the interpretation requires some caution) or is it several levels, and hence more robust. Or perhaps this is the resolution of the climate model, rather than the parent dataset? From Fig 1a it looks as though it may be two levels, but still it is unclear whether that is the climate model or dataset resolution.

This is a very good point. Mohan Gupta from FAA assured us that the shift of flight altitude in the Volpe future scenario is realistic and caused by the fact that new aircraft are expected to fly at a higher altitude than the older ones with the height difference ranging between 0.3-1.5km. We received the inventory horizontally and vertically gridded (with 30 vertical levels) from C.-C. Chen, NCAR, and find a vertical shift of air traffic, causing the maximum of air traffic distance in 2050 to be located at 200 hPa instead of 240 hPa as in the inventory for 2006. This shift from 200 to 240 hPa amounts to about 1 km height and is therefore consistent with the shift of between 0.3 and 1.5 km.

We added "The AEDT flight inventory that we use in our model has originally a 1°x1° horizontal resolution with 30 vertical levels, transformed by recursive conservative mapping (Jöckel, 2006) to our model resolution." and "… shift upwards by between 0.3 and 1.5 kilometers (pers. comm. M. Gupta, FAA), resulting in the shift of maximum flight density seen in Fig. 1a.".

5:5 Presumably there is a slight inconsistency here in that the HadGEM SSTs would have been forced by more than just changes in CO2?

Yes, this is true. We considered here only the change in CO_2 and SST as they are responsible for a major part of the change in the upper troposphere and lower stratosphere, the area where contrails form.

We added in "Other than that emissions and boundary data are not changed."

M4:28 – 5:3 I didn't find the simulation names very intuitive, especially 2006P when it is really 2050, and this inhibited understanding of the paper. I wonder if something like 2050T (T for traffic), 2050TC (C for climate), 2050TCS (S for soot or maybe M for modified efficiency and fuels) would help the reader more?

The year in the scenario name indicates the climate state in the model. We changed scenario names in order to make them more intuitive. They are now C2006-T06, C2006-T50, C2050-T50 and C2050-T50M (with "C" for climate, "T" for traffic and "M" for mitigation).

M6:4 – 6:8 This should be explained more clearly. I eventually understood that "slant" meant in the vertical rather than horizontal dimension and that "track distance" and "ground projected" were the same thing. The paper does not clearly say that "slant" is better, but this is what I assume. That led me to wonder whether the global estimates in this paper should be multiplied by the factor of 1.14 to give a more reliable answer.

Yes, the slant distance is the more realistic one, as we could initialize the contrails in a model gridbox with the exact length and volume, for explanation and discussion see Sect. 2.2. Unfortunately we do not have the slant distance numbers for the 2050 scenario. When we assume that the factor from track distance to slant distance stays constant in future scenarios we can apply it to the result we got for the 2050 scenario.

We repeated in Sect. 3.1 the definition of track and slant distance and added: "The results are based on an air traffic inventory of future air traffic measured as track (ground projected) distance rather than slant (3D) distance. Assuming that the relation of contrail cirrus radiative forcing calculated from track or slant distance stays constant for future scenarios and therefor applying the factor 1.14 (Bock and Burkhardt, 2016b), this would correspond to a global mean contrail cirrus radiative forcing of 182 mWm^{-2} that would be resulting from an inventory of future air traffic measured in slant distance. " We added this rounded value in the abstract and the extrapolated values for all scenarios in the Tab. 1.

6:21-6:22 I found this unclear, even having worked in the area, and suggest the text is expanded to make it clearer. Is the "formation threshold" referring to a temperature or supersaturation threshold or both?

As we only study persistent contrails forming within ice supersaturated air, the formation criterion (Schmidt-Appleman criterion) is a temperature criterion.

We modified this part: “It needs to be pointed out that contrail optical depth is likely overestimated in the tropics, since in the tropics contrails form within a few degrees of the temperature threshold (Schmidt-Appleman criterion) limiting ice nucleation in the contrail (Bier and Burkhardt, 2019), a process that is not resolved in our simulations (Sect. 2.3). Therefore optical depth and lifetimes of contrails will be overestimated (Burkhardt et al., 2018) and consequently radiative forcing.”

6:23 and 6:26: Sentences repeated? Also point out to the reader (6:23) that the ice supersaturation is not shown?

Thanks. We deleted the second sentence and added “(not shown)” in the text.

M7:5 The “shift of a large fraction” is interesting/ important but too vague. Could this be made quantitative? Presumably it differs between summer and winter, as the tropopause itself changes so much in mid-latitudes. Or perhaps this has been discussed in another paper and a reference could be given?

In the absence of a diagnostic in our model output giving us the shift into the stratosphere we calculate the shift relative to an annually mean tropopause. The fraction of air traffic above the mean tropopause in the midlatitudes (40 to 50°N) increases from 16 to 29% from 2006 to 2050. We added this information: “(in the northern midlatitudes the fraction increases on average from 16 to 29%)”.

7:26 Would “contrail formation frequency” be better described as the “probability of contrail formation”? The frequency is dependent on an aircraft flying through the relevant grid box and so could be zero even if the probability is 1.

We corrected the figure caption of Fig. 5 to “persistent contrail formation probability” and changed it in the text.

9:9 NORTHERN extratropics

Thanks.

9:14 Strictly I think this is the cold ice supersaturation frequency – as I understand it, it is the warming, rather than the humidity change, that is most influential in changing the tropics

We agree that the main reason for the changes in the tropics is the warming and we tried to clarify this statement with adding “caused mainly by temperature changes “ to the text.

9:25 Add “global-mean” to this sentence.

Yes, we did.

M10.3 If estimates of aviation CO2 radiative forcing from the 2 AEDT scenarios (or the CO2 amounts - as the forcing could be derived from the simple IPCC expresssions) are easily available from other papers, their addition here (and the relative growth from 2006) would be useful to place the growth of the contrail forcing in perspective. It would be particularly useful to know if the contrail forcing grows more/less rapidly than the CO2 forcing. This may need a further caveat given the Ponater et al. (Atmos Env 2006) and Rap et al. (GRL 2010) papers indicating that the efficacy of contrail forcing may be significantly less than 1.

To include this interesting point in our paper we added a two paragraphs to the conclusion:

“In order to understand the implications of our results for the overall air traffic climate impact, we calculated the aviation CO_2 radiative forcing according to Myhre et al. (1998). CO_2 emissions and contrail cirrus radiative forcing are the two largest aviation related radiative forcing components besides the possibly large but as yet unquantified impact of indirect effects on clouds (Lee et al., 2009). Radiative forcing due to aviation CO_2 emissions amounts for 2006 to 24.0 mWm^{-2} and for the year 2050, assuming the C2050-T50 scenario, to 84.8 mWm^{-2} and assuming the C2050-T50M scenario to 58.0 mWm^{-2}. This means that the factor of increase in CO_2 radiative forcing from C2006-T06 to C2050-T50 is 3.5, slightly higher than 3.2 for the contrail cirrus radiative forcing. Considering the increase in fuel efficiency from C2006-T06 to C2050-T50M, the factor of change for the CO_2 radiative forcing is reduced to 2.4, whereas the factor of change for the global contrail cirrus radiative forcing in this scenario is reduced to 2.8. The decrease in contrail cirrus radiative forcing in this scenario is caused by the decrease in soot emissions. This means that radiative forcing due to contrail cirrus can be expected to increase faster in the future than that due to CO_2.

The increase in fuel efficiency included in the AEDT inventory does not conform with the CORSIA agreement unless a large part of the CO_2 emission reduction is reached by carbon offsetting. It is important to point out that carbon offsetting deals only with the impact of CO_2 emissions while leaving the impact of contrail cirrus on climate unchanged. Since the increase in contrail cirrus radiative forcing can be stronger than in CO_2 radiative forcing both radiative forcing components need to be considered in future agreements.”

As we calculate contrail cirrus radiative forcing and give no implications to surface temperature, we do not want to open the discussion about efficacy of contrail cirrus in this paper.

Figure 1: In (a) the (a) label obscures the lines. Also the y-axis is pressure not height

Thanks. We modified the figure.

Figure 2 (a) caption says km per year but the y-axis label says km per second. I note that the labels (US/Mexico and East China/Japan) differ between here and Fig 4, and the text itself. I suggest making consistent.

I suppose you meant Fig. 3. Indeed we show the flight distance in km/s, therefor we changed the figure caption. Regarding the regions, we updated Fig. 4 with the consistent names.

M:Figure 3 needs some work to help the reader. On initial viewing it is indigestible. Yaxis labels are missing, when they need not be, and their addition would make it much clearer. It is also here that I most felt a more intuitive use of simulation names would help the reader. "2006 plus" feels particularly unhelpful.

We hope we could clarify more with adding the y-axis labels and renaming the scenarios (see earlier comment).

Figure 5: The power of 10 labels are unreadable to me. Could they be removed from the figure and included in the caption instead?

Thanks. We did.

Typos etc

1:26 "live time" -> "lifetime"

Thanks.

2:28 Irvine et al. missing from reference list, unless this meant to be Irvine and Shine

Thanks.

4:11 and 11:23 Barret -> Barrett

Thanks.

5:11 I advise using x not * for multiplying factors of 10 - see also Table 1 (maybe irrelevant if dealt with at the typesetting stage)

Thanks.

5:24 – 5:26 The O's are for Ost?

Thanks.

10:6 Section 4 not 5?

Thanks.

Contrail cirrus radiative forcing for future air traffic

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Abstract. The climate impact of air traffic is to a large degree caused by changes in cirrus cloudiness resulting from the formation of contrails. Contrail cirrus radiative forcing is expected to increase significantly with time due to the large projected increases in air traffic. We use ECHAM5-CCMod, an atmospheric climate model with an online contrail cirrus parameterization including a microphysical two-moment scheme, to investigate the climate impact of contrail cirrus for the year 2050. We take into account the predicted increase in air traffic volume and changes in propulsion efficiency and emissions, in particular soot emissions, and the modification of the contrail cirrus climate impact due to anthropogenic climate change.

Global c~~C~~ontrail cirrus radiative forcing increases by a factor of 3 from 2006 to 2050 reaching 160 or even 180 mWm^{-2}, resulting from the increase in air traffic volume and a slight shift of air traffic towards higher altitudes. Large increases in contrail cirrus radiative forcing are expected over all of the main air traffic areas but relative increases are largest over ~~South-East Asia/India and Eastern China/Japan~~main air traffic areas over Eastern Asia. The projected upward shift of air traffic attenuates contrail cirrus radiative forcing increases in the mid-latitudes but reinforces it in the tropical areas. Climate change has an insignificant impact on global contrail cirrus radiative forcing while regional changes are significant. Of the emission reductions it is the soot number emission reductions by 50% that lead to a significant decrease in contrail cirrus optical depth and coverage, leading to a decrease in radiative forcing by approximately 15%. The strong increase in contrail cirrus radiative forcing due to the projected increase in air traffic volume cannot be compensated for by the decrease in initial ice crystal numbers due to reduced soot emissions and by improvements in propulsion efficiency.

1 Introduction

Air traffic has contributed approximately 5% to the anthropogenic climate forcing in 2005 (Lee et al., 2009), and its contribution is rising due to the large yearly increases in air traffic (ICAO, 2007). Radiative forcing due to contrail cirrus, consisting of linear contrails and the cirrus clouds arising from them, is the largest known radiative forcing component associated with air traffic, larger than that due to CO_2 accumulated from aviation (Burkhardt and Kärcher, 2011). Contrail cirrus are central for mitigation efforts due to their short life~~ve~~ time by, for example, varying flight ~~height~~level, path or timing or using alternative fuels, new engine designs or other technological advances (e.g. Noppel and Singh, 2007; Lee et al., 2010; Newinger and Burkhardt, 2012; Deuber et al., 2013; Burkhardt et al., 2018). Both, their large climate impact and their suitability for mitigation underline the importance of investigating contrail cirrus for future air traffic scenarios.

The climate impact of contrail cirrus in the future is determined by a number of factors: the strength and geographic distribution of the increase in air traffic volume, improved fuel efficiency, changes in aircraft emissions when using alternative fuels and the change in the background atmospheric state due to future climate change. Several projections for future air traffic volume and its emissions exist. According to ICAO (2007) and Airbus (2007) passenger flown distance is expected to double roughly every 15 years. The air traffic inventory AEDT (Wilkerson et al., 2010) estimates that in 2050 the air traffic volume will have quadrupled relative to the year 2006. The distribution of air traffic as well as its future increase is globally very uneven. In 2006 93% of aviation fuel was burned in the Northern Hemisphere and 69% between 30° and 60°N. More than half of global aviation CO_2 is emitted over three regions: the United States (26%), Europe (15%) and East Asia (11%) (Wilkerson et al., 2010). Due to historically low air traffic densities in the tropics, the relative increases are expected to be much larger in the tropical areas than in the extratropics.

Lee et al. (2009) estimate that fuel usage is expected to increase between 2000 and 2050 by a factor of 2.7 to 3.9, depending on the IPCC SRES scenario while AEDT estimates an increase by a factor of 2.7 to 5 between 2006 and 2050 (Chen and Gettleman, 2016). Aerodynamic changes, weight reductions, more fuel efficient engines and an increased operational efficiency lead to increased overall fuel efficiency (Lee et al., 2009). ICAO (2007) expects a fuel efficiency improvement of 2% per annum until 2050. Increasing fuel efficiency of engines leads to an increase in the contrail formation probability and contrail radiative forcing (Marquart et al., 2003).

Measurements behind aircraft (Beyersdorf et al., 2014; Moore et al., 2017) show that the combustion of an alternative fuel, a blend of Jet A and Fisher-Tropsch fuel, induces a decrease in the mass and number of soot particles. This results in a lower number of nucleated ice crystals (Kärcher and Yu, 2009; Kärcher et al., 2015) and in a higher survival rate of ice crystals during the contrail's vortex phase (Unterstrasser, 2016). The change in the ice crystal number after the vortex phase has an impact on the microphysical process rates and the evolution of contrail cirrus (Bier et al., 2017) with ice crystals growing to larger sizes and sedimentation initiated earlier in the life cycle. This leads eventually to a decrease in~~ing~~ the mean optical depth and life time of contrail cirrus (Burkhardt et al., 2018). This is particularly important in large scale and long lived contrail cirrus clusters (Bier et al., 2017), which are responsible for a large part of the contrail cirrus radiative forcing (Burkhardt et al., 2018).

With climate change caused by increasing greenhouse gas concentrations, contrail cirrus formation and properties may change. The increase in temperature may lead to a lower contrail formation probability in particular in the tropics and in summer in the subtropics (Marquart et al., 2003). An increase in atmospheric water vapour concentration may lead to higher contrail cirrus ice water content and optical depths. A decrease in the ice supersaturation frequency (Irvine and Shine~~et al.~~, 2015) may result in lower contrail cirrus coverage and associated radiative forcing.

The radiative forcing of line-shaped contrails (the contrails that have retained their initial line-shape and are, therefore, easily distinguishable from natural clouds in satellite images) and contrail cirrus for the year 2050 has been studied in a number of publications. Minnis et al. (1999) estimate a radiative forcing due to line-shaped contrails for the year 2050 of 100 mWm^{-2} when assuming a constant visible optical depth of 0.3~~ and 60 mWm^{-2} for varying optical depth~~. In Marquart et al. (2003) line-shaped contrail radiative forcing increases from 2015 to 2050 by a factor of approximately 1.6 amounting to 15 mWm^{-2} in the year 2050 or after a suitable correction for a low bias in optical depth to about 45 mWm^{-2} (Kärcher et al., 2010). For contrail cirrus, comprising of line-shaped contrails and the clouds developing from them, Lee et al. (2009) scaled present-day radiative forcing estimates, from models and observations, to 2050 arriving at a range between 27 and 315 mWm^{-2} with no best estimate given. Chen and Gettelman (2016) studied the change in cirrus cloudiness due to contrail formation using a model in which contrail formation is treated as a source term for cirrus ice crystals and the model microphysics is applied to a mix of contrail and natural cirrus ice crystals. They estimated that contrail cirrus radiative forcing increased by a factor of 7 from 2006 to 2050, reaching 87 mWm^{-2} in the year 2050, a factor that is approximately double the factor of increase in air traffic volume. They argued that this is caused by the non-uniform regional increase in air traffic and different sensitivities of contrail cirrus radiative forcing to an increased air traffic volume in different regions.

Our aim is to estimate contrail cirrus radiative forcing for the year 2050 globally and regionally, isolating changes due to the increase and upward shift in air traffic volume, due to climate change and due to changes caused by the use of alternative fuels and changes in the propulsion efficiency. We use the atmospheric general circulation model coupled with a contrail cirrus scheme, ECHAM5-CCMod (Bock and Burkhardt, 2016a; Sect. 2.1), which treats contrail cirrus as an independent cloud class. The model simulates the whole life cycle of contrail cirrus and resolves the competition of the two cloud classes, natural clouds and aircraft induced clouds, for water vapour. We apply ECHAM5-CCMod to future aviation emission scenarios from the AEDT inventory (Sect. 2.2) and estimate contrail cirrus coverage, optical depth and radiative forcing for air traffic for the year 2050 (Sect. 3). Discussion and conclusions are given in Sect. 4 and 5.

2. Model and data

2.1 CCMod in ECHAM5

We use a contrail cirrus scheme developed for ECHAM5 (Bock et al., 2016a) which is based on the contrail scheme of Burkhardt et al. (2009) and the two-moment microphysical scheme of Lohmann et al. (2008). The scheme introduces a new cloud class, contrail cirrus, in the ECHAM5-HAM model (Roeckner et al., 2003; Stier et al., 2005) with contrail cirrus modifying the atmospheric heat and water budget, thus feeding back on natural clouds (Burkhardt et al., 2011). The prognostic variables in the parameterization are contrail cirrus cover, volume and length, ice water content and ice crystal number concentration. Contrail cirrus properties change due to the following parameterized processes: contrail formation, contrail cirrus volume growth due to turbulent diffusion and sedimentation, contrail spreading due to vertical wind shear, water vapour deposition and sublimation on contrail ice crystals, contrail ice crystal sedimentation and precipitation and indirectly due to contrail induced changes in the diabatic heating rates. Contrail cirrus form according to the Schmidt-Appleman criterion (Schumann et al., 1996) and persist in ice supersaturated regions which are parameterized in the model

(Burkhardt et al., 2008; Lamquin et al., 2012). Contrail cirrus are initialized with the air traffic density (distance per grid box) and water vapour emissions prescribed by an air traffic inventory and with an ice crystal number concentration and a contrail cross sectional area inferred from observations (Bock and Burkhardt, 2016a). If persistent, contrails spread and accumulate more ice from ambient water vapour as long as supersaturation prevails. Contrail cirrus gradually vanish through ice crystal sedimentation into subsaturated areas and through sublimation. Hence, the whole life cycle of contrail cirrus is simulated.

We calculate total contrail cirrus coverage assuming a maximum random overlap of contrail cirrus in the vertical for each column (Burkhardt and Kärcher, 2011). This implies that contrail cirrus coverage above or below other cirrus overlaps maximally, whereas contrail cirrus that is vertically separated from other cirrus by cloud free air overlaps randomly. We estimate the stratosphere adjusted radiative forcing, that is the change in the radiation flux at the top of the atmosphere, after the stratosphere has reached a new radiative balance (Hansen et al., 1997).

2.2 Inventory

The gridded aviation emissions database, developed at the Volpe National Transportation Center using the U.S. Federal Aviation Administration Aviation Environmental Design Tool (AEDT) (Roof et al., 2007; Barrett et al., 2010), is composed of one base case for the year 2006 (**2006**), which has been compared against other aviation emissions data sets (Wilkerson et al., 2010), and two future 2050 scenarios. The latter include the projected increase in air traffic (**2050 Baseline**), which is based on the IPCC FESG (Forecasting and Economic Analysis Sub-Group) consensus demand forecast (FESG, 1998), and additionally an increase in ~~the propulsion~~ fuel efficiency by 2% per year (**2050 Scenario 1**). As fuel burn increases by a factor of 4.8 between 2006 to 2050 Baseline and still by a factor of 2.7 between 2006 and 2050 Scenario 1 (Unger et al., 2013), the specifications of the future projections do not meet the requirements of the international CORSIA agreement unless the remaining necessary CO_2 emission reductions are introduced purely by carbon offsetting.

The AEDT flight inventory that we use in our model has originally a 1°x1° horizontal resolution with 30 vertical levels, transformed by recursive conservative remapping (Jöckel, 2006) to our model resolution. We use inventory data of air traffic density (distance per grid box) and water vapour emissions to initialize contrails in the model. The flight path distance for 2050 Baseline and 2050 Scenario 1 is only provided as monthly mean aggregated ground projected path distance per grid cell (track distance). Therefore, we could not use the 3D flight path distance per grid cell (slant distance) as in Bock and Burkhardt (2016b), which results in an underestimation of the initial volume and ice crystal number of contrails and, therefore, of the total contrail cirrus radiative forcing (Bock and Burkhardt, 2016b). But we scale the resulting radiative forcing estimates using a factor calculated from radiative forcing for contrail cirrus when using slant distance and using track distance for the year 2006 (Bock and Burkhardt, 2016b).

Flight distance is expected to increase between 2006 and 2050 by approximately a factor of 4 (Table 1). Due to changes in aviation technologies flight altitudes are expected to shift ~~slightly~~ upwards by between 0.3 and 1.5 kilometres (pers. comm. Mohan Gupta, FAA), resulting in the shift of maximum flight density seen in Fig. 1a. In 2006 air traffic is largest at about

240 hPa, whereas in 2050 air traffic is predicted to be largest at about 200 hPa~~ (Fig. 1a)~~. The regional distribution of air traffic for 2050 is expected to remain close to the distribution for 2006 with main air traffic maxima over Europe and the U.S. (Fig. 1c). Additionally to those air traffic maxima, air traffic over Eastern and Southeastern Asia is strongly increased. Maxima in zonal mean aircraft density remain between 30 and 50°N (Fig. 1b).

2.3 Simulation setup

We have performed the following simulations:

- a control simulation for the air traffic of 2006 (simulation **C2006-T06**);
- a simulation with increased air traffic according to the AEDT projection of air traffic for the year 2050 (simulation C**2006-T50** ~~**Plus**~~);
- a simulation that additionally accounts for a changed background climate in 2050 (simulation **C2050-T50** ~~**Baseline**~~);
- a simulation that considers additionally an increase in fuel and propulsion efficiency as well as a change in emissions connected with the use of renewable alternative fuel, in particular a reduction in soot emissions by 50%, and a slight increase in the water emission coefficient connected with the use of alternative fuels (simulation **C2050-T50M** ~~**Scenario 1**~~).

The specifications for the different simulations are summarized in Table 1.

All simulations were performed over 5 years with ECHAM5-CCMod at T42L41 resolution with a time step of 15 minutes. The CO_2 mixing ratio is prescribed for the respective base year (381ppm for the year 2006 and 478ppm for the year 2050 following the RCP 6.0 (Meinshausen et al., 2011)). The annual cycle of sea surface temperature and sea ice concentration were taken from the AMIP II database for the year 2006 and from simulations with the Hadley Centre Global Environment Model version 2 - Earth System (HadGEM2-ES) Model (Jones et al., 2011) following the Representative Concentration Pathway (RCP) 6.0 for the year 2050. Other than that emissions and boundary data are not changed. In order to calculate the contrail formation criterion we prescribe the emission index of water vapour to be 1.21 kg-H_2O per kg-fuel and the combustion heat 43x~~*~~10^{6}~~M~~J/kg (Chen et al., 2012). The radiation scheme is called every half hour calculating radiative transfer with and without contrail cirrus (see Bock and Burkhardt (2016b) for details).

Using alternative aviation fuels reduces soot emissions in terms of mass as well as of particle number (Moore et al., 2015, 2017). This in turn leads to a reduction in ice crystal nucleation within contrails (Kärcher et al., 2015) and to a reduction in the ice crystal loss in the vortex phase (Unterstrasser, 2016). Additionally, using alternative fuels causes a slight increase of the water emission coefficient by 15% (Moore et al., 2017). In our study we initialize contrails at a contrail age of ~7 min with a contrail cross sectional area of 200×200 m and an ice crystal number concentration of 150 cm^{-3}, a value derived from in situ measurements of young contrails after the vortex phase (~~Febvre et al., 2009; Schröder et al., 2000; Voigt et al., 2011;~~ Bock and Burkhardt, 2016a), neglecting the variability due to the influence of the atmospheric state on ice crystal nucleation and ice crystal loss within the contrail's vortex phase. In simulation 2050 Scenario 1 we assume that a 50% reduction in soot emissions causes a 50% reduction in the initial ice crystal number.

We analyse the change in contrail cirrus properties in different areas defining four equally sized regions of high air traffic density, the U.S./Mexico (20-45°N, 235-290°E~~O~~), Europe (35-70°N, -20-35°E~~O~~), South East Asia/India (-10-20°N, 70-110°E~~O~~) and Eastern China/Japan (20-45°N, 95-150°E~~O~~). Additionally two latitude bands (with different areal coverage) representing different background climate conditions are compared, the tropics (0-30°N) and midlatitudes (40-70°N) (see Fig. 1c and d).

3. Results

In this section we describe the change in simulated contrail cirrus properties and radiative forcing prescribing air traffic for the years 2006 and 2050. We distinguish between changes resulting only from the increase in air traffic and its upward shift, and from increasing air traffic within a changed climate state. Finally we discuss an additional change in propulsion efficiency and aircraft emissions.

3.1 Air traffic for the year 2006

Our simulation for the year 2006 which we use as a reference has already been described in detail in Bock and Burkhardt (2016b). Differences between the simulation presented here and in Bock and Burkhardt (2016b) are due to the fact that we use here track distance as a measure for aircraft flight movements (Sect. 2.2). Using the 3d flight path distance per grid cell (slant distance) instead of the ground projected distance (track distance) leads to an increase in global air traffic volume by 1.8 with increases being largest at lower levels and over Europe and northern America. The radiative forcing due to air traffic in the year 2006 using the ground projected estimate for air traffic distance amounts to approximately 49 mWm^{-2} (Fig. 2; see also Bock and Burkhardt, 2016b, Table 1), whereas the radiative forcing estimate using slant distance is larger by a factor of 1.14 (Bock and Burkhardt, 2016b).

Of the four equally-sized air traffic areas indicated in Fig. 1c and Fig. 2, flight density is largest over the U.S./Mexico and second largest over Europe for the year 2006 (Fig. 3a). Consistently, the maxima of contrail cirrus coverage are over U.S./Mexico and Europe (Fig. 4 d) and the contribution to global contrail cirrus radiative forcing is largest from these two regions and amounts to 27% and 18%, respectively (Fig. 3b). Contrail cirrus radiative forcing per flight distance is significantly larger over Europe than over the U.S./Mexico, ~~although~~ and optical depth is larger over the U.S./Mexico (Fig. 4 e and f). This is in agreement with the fact that a large portion of the contrail cirrus coverage over Europe is due to aged contrail cirrus reinforced by contrail cirrus transported into Europe from the Atlantic air traffic corridor. The contribution of contrail cirrus radiative forcing from the South East Asia/India region to global mean radiative forcing is low (Fig. 3b), about 5%, but relative to the air traffic distance flown in the area very high (Fig. 3c). In this area the ice supersaturation frequency is very high (Lamquin et al., 2012) leading to a high probability of contrail formation and the amount of water vapour available for deposition is large, leading to a high optical depth (Fig. 4e and f; Bock and Burkhardt, 2016b). It needs to be pointed out that contrail optical depth is likely overestimated in the tropics, since in the tropics contrails form within a few degrees of the temperature threshold (Schmidt-Appleman criterion) limiting ice nucleation in the contrail (Bier and Burkhardt, 2019), a process that is not resolved in our simulations (Sect. 2.3). Therefore optical depth and lifetimes of contrails will be overestimated (Burkhardt et al., 2018) and consequently radiative forcing. ~~It is important to point out that contrail optical depth is to a large degree controlled by the number of ice crystals formed in the contrail (Burkhardt et al., 2018, Bier et al., 2017) and that this number may be reduced in the tropics due to contrail formation close to the formation threshold (Kärcher et al., 2015) leading to lower optical depth than estimated here.~~ On average, ice supersaturation frequencies (not shown) and contrail cirrus radiative forcing is in the whole tropical belt smaller than over South East Asia/India.

Contrail cirrus in the tropics are estimated to have a smaller radiative impact, absolute and per flight distance, than in the mid-latitudes (Fig. 3b and c). ~~Ice supersaturation frequencies are on average smaller than over South-East Asia.~~ The radiative impact per contrail cirrus coverage (not shown) is in the tropics larger than in the extratropics due to the larger specific humidity that leads to a larger optical depth than in the extratropics (Fig. 4e and f).

3.2 Increased air traffic

The increase in global air traffic volume, including the shift to higher altitudes (Sect. 2.2), leads to a large increase in contrail cirrus radiative forcing (Table 1, Fig. 2). While the global flight distance increases from 2006 to 2050 by a factor of about 4, the global radiative forcing increases from 49 to 159 mWm^{-2}, by a factor of about 3. The global pattern of contrail cirrus radiative forcing changes only slightly, with maxima over eastern and south-eastern Asia gaining in importance (Fig. 2). Spatial differences in the increase of contrail cirrus radiative forcing are largely due to the unequal global distribution of the increase in flight distance and due to differences in the response to shifting air traffic to higher altitudes and due to saturation effects.

The shift in air traffic to higher altitudes leads in the mid-latitudes to a shift of a large fraction (in the northern midlatitudes the fraction increases on average from 16 to 29%) of air traffic into the stratosphere, where fewer persistent contrails can form due to the lower atmospheric humidity. Therefore, the increase in radiative forcing is substantially smaller than in flight distance, leading to a strong decrease (~37%) in contrail cirrus radiative forcing per flight distance in the mid-latitudes (Fig. 3c). This decrease is most pronounced over Europe (amounting to ~48%), our most northern analysed area. Over the U.S./Mexico and Eastern China/Japan, radiative forcing per flight distance decreases similarly, by about 30%.

In the tropics, the upwards shift of air traffic leads to a larger probability of contrail formation. Contrail formation at lower air traffic altitudes in the tropics is mostly limited by temperature which is too high for contrail formation (Burkhardt et al., 2008). Shifting air traffic in the tropical troposphere upwards, towards lower temperature conditions, thus leads to a higher probability of contrail formation. This change in contrail formation probability together with the increase in flight distance leads to a large increase in contrail cirrus radiative forcing (Fig. 3b). The radiative forcing per flight distance decreases slightly but remains larger in South East Asia/India than in all other areas (Fig. 3c). The largest relative increase in flight distance and contrail cirrus radiative forcing is expected in the region of East China/Japan and Southeast Asia/India (Fig. 4a) but their absolute contribution to global contrail cirrus radiative forcing still remains far smaller than those from the U.S./Mexico and from Europe (Fig. 3b).

3.3 Climate change

We calculate contrail cirrus properties and radiative forcing for air traffic for the year 2050 within a warming climate in our C2050-T50~~ Baseline~~ simulation. The background meteorology in 2050 is assumed to change according to the RCP 6.0 scenario. The RCP scenario does not include the climate impact of contrail cirrus. In a changed climate we estimate contrail cirrus radiative forcing to amount to 160 mWm^{-2} (Table 1). The net impact of climate change on global contrail cirrus radiative forcing for the year 2050 is not significantly different from zero.

Figure 5a shows the zonal mean changes in probability of persistent contrail formation~~ frequency~~ from 2006 to 2050 meteorology. Whereas north of about 30° to 40°N the probability of persistent contrail formation~~ frequency~~ increases above 250hPa, it decreases in the tropical regions between 100 and 300 hPa. This leads to a slight decrease in contrail cirrus coverage and radiative forcing in the tropical areas (by ~5%) and over Eastern China/Japan (by ~20%) (Fig. 4b and d). The contrail cirrus cover decreases in the Eastern China/Japan region (Fig. 4d) due to a lower ice supersaturation frequency and a lower contrail formation probability~~less frequent formation of persistent contrails~~. This leads to a decrease in radiative forcing (Fig. 4b) and in radiative forcing per flight distance (Fig. 3c) over Eastern China/Japan. Over Europe and the U.S./Mexico contrail cirrus coverage and optical depth is slightly increased (by ~5%)~~. Our simulations show that contrail cirrus optical depth increases over the U.S./Mexico~~ (Fig. 4d,e and f), which leads to a slight increase in contrail cirrus radiative forcing over Europe and the U.S./Mexico (Fig. 4b). These two different effects, an increase of contrail cirrus radiative forcing over the U.S./Mexico and over Europe and a decrease over Eastern China/Japan and the tropical areas, almost compensate each other (Fig. 4b).

3.4 Reduced soot emission and improvement in propulsion efficiency

A reduction in the initial contrail ice particle number by 50% leads to a strong decrease in the climate impact of contrail cirrus reducing global radiative forcing for the year 2050 by 14% from 160 to 138 mWm^{-2} (Table 1). A smaller number of initial ice crystals can grow faster assuming a constant amount of ambient water vapour available for ~~condensation~~deposition, leading to an earlier and larger sedimentation loss of ice crystals (Bier et al., 2017) and therefore, to a decrease in contrail cirrus optical depth, life times and radiative forcing (Burkhardt et al., 2018). The decrease in contrail cirrus radiative forcing for the year 2050 is caused by a decrease in contrail cirrus optical depth of up to 30% (Fig. 4 e and f, Fig. 6) and a decrease in contrail cirrus coverage (Fig. 4d). The changes in radiative forcing are largest over South East Asia/India where sedimentation plays a greater role due to the larger amount of water vapour available for ~~condensation~~deposition. Over Europe the effect is slightly larger than over the U.S./Mexico, because of its location downwind of the North Atlantic flight corridor where contrail cirrus coverage is strongly influenced by the life time of contrail cirrus originating over the Atlantic. The smallest impact of the reduction in initial ice crystal numbers on contrail cirrus radiative forcing among the four studied regions can be found over the U.S./Mexico (Fig. 4c) where contrail cirrus coverage mainly consists of young contrails.

The impact of soot reductions is smaller than estimated in Burkhardt et al. (2018) who found that a 50% reduction in soot emissions causes a 20% reduction in contrail cirrus radiative forcing for air traffic of the year 2006. The difference in sensitivity may be caused by the change in air traffic volume and pattern. Contrail cirrus radiative forcing is nonlinearly dependent on the initial ice crystal number (Burkhardt et al., 2018). This means that reducing initial ice crystal numbers in an increased air traffic environment has a smaller impact on contrail cirrus radiative forcing than for current air traffic since an abundance of contrail cirrus ice crystals will still exist even if nucleation rates are reduced.

The increase in propulsion efficiency and the change in water vapour emissions (Sect. 2.3) has no significant impact on contrail cirrus radiative forcing. Only in the tropics persistent contrail formation probability around 250 hPa is slightly increased (Fig. 5b), which has no significant impact on the global radiative forcing due to contrail cirrus.

4. Discussion

Only one study exists that analyses the impact of contrail cirrus on the radiative balance in the future and another study looks at the change in line-shaped contrails only. Chen and Gettleman (2016) use a very different approach simulating contrail cirrus, calculating the number of newly formed contrail ice crystals from the available water vapour, setting the size of the ice crystals constant, and feeding this tendency in ice crystal number into the natural cloud scheme. Their resulting estimate of contrail cirrus radiative forcing for the year 2006, 13 mWm^{-2}, is significantly smaller than our estimate which is likely connected with an underestimation of ice crystals formed at contrail formation resulting from assumed ice crystals sizes larger than observed in young contrails (Schumann and Heymsfield, 2017). Due to the 4 fold increase in air traffic they estimate an increase in contrail cirrus radiative forcing by a factor of 7, which they argue is caused by non-uniform increases in air traffic and regional differences in sensitivity to air traffic. We calculate a 3 fold increase in contrail cirrus radiative forcing connected with the 4 fold increase in air traffic which is in line with the 3 fold increase in contrail cirrus coverage predicted by our model. Finally Chen and Gettelman (2016) estimate a decrease of contrail cirrus radiative forcing by about 12% and 8% assuming RCP 8.5 and RCP 4.5, respectively, whereas we find that regionally significant changes in contrail cirrus radiative forcing due the changing climate (assuming RCP 6.0) cancel out globally. This difference in the impact of climate change on contrail cirrus radiative forcing is caused by differences in the estimated ~~of the~~ change in the persistent contrail formation probability ~~frequency~~ (Fig. 5a). ~~Whereas t~~The decrease in contrail formation probability in the tropics, caused mainly by temperature changes, is captured by both models.~~,~~ I~~i~~n the northern extratropics we find an increase in the persistent contrail formation probability~~frequency~~ in about 250 to 350 hPa which lies ~~further to the south~~north of 40°N whereas~~ than~~ in the simulations of Chen and Gettelman (2016, their Fig. 2) this increase is found further north starting at 60°N. ~~and t~~Thus in our simulation the increase in contrail formation probability still effects contrail formation over the U.S./Mexico region. This leads in our study to a cancellation of the decrease in contrail formation in the tropics and an increase in the extratropics due to climate change at main flight levels. The disagreement in the extratropics is not unexpected as f~~F~~uture changes in contrail cirrus properties and radiative forcing due to a changing climate are much more uncertain in the mid-latitudes than in the tropics since the trend in ice supersaturation frequency in the mid-latitudes is strongly model dependent (Irvine and Shine, 2015).

Marquart et al. (2003), who study only line-shaped contrails, use an approach that relies on the scaling of the contrail formation probability over a specified area to observations~~,~~. They show a strong decrease of line-shaped contrail coverage in the tropics due to climate change of~~by~~ up to 70%. Their method is connected with a number of weaknesses, firstly an error in the parameterization of potential contrail coverage which is effective especially in the tropics (Burkhardt et al., 2008), assumptions about the scalability of contrail cirrus coverage (Burkhardt et al., 2010) that assume contrail cirrus life cycles to be equal in the extratropics and tropics which is not justified (Burkhardt et al., 2018) and the assumption that scaling coefficients can be transferred from our to a future climate.

However, all studies agree that increasing air traffic is the dominating effect that causes higher global mean contrail cirrus radiative forcing in the future and the Chen and Gettelman study and our study agrees on the change in climate having only a small impact on global mean contrail cirrus radiative forcing.

Contrail cirrus radiative forcing per flight distance appears to be particularly high in the tropics. This result should still be viewed with some caution, since in the tropical areas contrails form close to the threshold conditions which lead to a lower contrail ice crystal nucleation rate which has implications not only for contrail optical depth but also for the ice crystal loss rates during the vortex phase, microphysical process rates and contrail cirrus life times (Bier et al., 2019). When including a parameterization for contrail ice crystal nucleation this is likely to lead to a decrease in contrail cirrus radiative forcing in the tropics. The impact of the tropical areas on global contrail cirrus radiative forcing is still very limited so that the overestimation of contrail cirrus ice crystals has a limited impact on global contrail cirrus radiative forcing. As air traffic increases strongly in the tropical areas future simulations should include the impact of lower nucleation rates and the associated changes in ice crystal loss rates, changes in optical depth, microphysical process rates and contrail cirrus life time in the tropics.

5. Conclusion

In this paper, we present contrail cirrus properties and radiative forcing for the year 2050 using AEDT emission scenarios. We isolate effects that can be expected from the change in air traffic volume and its geographic and vertical distribution, from climate change, from improvements in fuel and propulsion efficiency and decreases in soot and water vapour emissions, caused by the use of alternative fuels. We study regional changes in the main air traffic areas and in areas where air traffic is projected to increase strongly.

We find that the future projected increase in air traffic and the slight shift to higher altitudes leads to a large increase of contrail cirrus coverage, optical depth and radiative forcing. With a four-fold increase in air traffic contrail cirrus radiative forcing is increasing three-fold, from 49 to 159 mWm^{-2}. The results are based on an air traffic inventory of future air traffic measured as track (ground projected) distance rather than slant (3D) distance. Assuming that the relation of contrail cirrus radiative forcing calculated from track or slant distance stays constant for future scenarios and therefor applying the factor 1.14 (Bock and Burkhardt, 2016b), this would correspond to a global mean contrail cirrus radiative forcing of 182 mWm^{-2} that would be resulting from an inventory of future air traffic measured in slant distance. The main air traffic areas over Northern America and Europe continue to contribute the largest fraction of the contrail cirrus radiative forcing but the Asian main air traffic areas gain in importance. Our estimates of current and future contrail cirrus radiative forcing are different to those given by Chen and Gettelman (2016) which is likely connected with their methodology estimating contrail ice nucleation (see Sect. 45). Contrail cirrus radiative forcing appears to be hardly affected by climate change assuming RCP 6.0, which leads to a slight decrease in contrail cirrus coverage and radiative forcing over Asia and a compensating small increase over Northern America and Europe. This is in contrast to results from Chen and Gettelman (2016) who found contrail cirrus radiative forcing to decrease due to climate change by about 12% assuming RCP 8.5. The reason for this discrepancy can be traced back to a difference in the pattern of change of contrail formation probability in the northern hemisphere. The maximum increase in contrail formation probability lies within the midlatitudes whereas in the Chen and Gettelman (2016) simulation it is found north of our maximum. Nevertheless, the studies agree that changes in contrail cirrus radiative forcing due to the projected increase in air traffic by far outweigh any damping effect that a change in climate may have.

Of the fuel and propulsion efficiency improvements and soot reductions due to the use of alternative fuels, it is the soot reduction that has the largest impact on contrail cirrus. The larger propulsion efficiency leads to a slight increase in the contrail formation probability in the tropics with little impact on global radiative forcing. The soot emissions cause a reduction in contrail cirrus optical depth and life time (Burkhardt et al., 2018) which leads again to a decrease in contrail cirrus coverage. Consequently contrail cirrus radiative forcing is decreased by 15%, less than estimated by Burkhardt et al. (2018) who infer a 20% reduction for air traffic in the year 2006. This slight decrease in sensitivity connected with soot number emission reductions is likely caused by the fact that the strong increase in air traffic leads to an abundance of ice crystals which makes decreases in ice crystal numbers less effective.

Overall the strong increase in radiative forcing from 2006 to 2050 due to larger air traffic volume and the shift of air traffic towards higher altitudes cannot be compensated by small reductions in radiative forcing due to changes expected from climate change, and projected reductions in reduced soot emissions and improvements in fuel efficiency.

In order to understand the implications of our results for the overall air traffic climate impact, we calculated the aviation CO_2 radiative forcing according to Myhre et al. (1998). CO_2 emissions and contrail cirrus radiative forcing are the two largest aviation related radiative forcing components besides the possibly large but as yet unquantified impact of indirect effects on clouds (Lee et al., 2009). Radiative forcing due to aviation CO_2 emissions amounts for 2006 to 24.0 mWm^{-2} and for the year 2050, assuming the C2050-T50 scenario, to 84.8 mWm^{-2} and assuming the C2050-T50M scenario to 58.0 mWm^{-2}. This means that the factor of increase in CO_2 radiative forcing from C2006-T06 to C2050-T50 is 3.5, slightly higher than 3.2 for the contrail cirrus radiative forcing. Considering the increase in fuel efficiency from C2006-T06 to C2050-T50M, the factor of change for the CO_2 radiative forcing is reduced to 2.4, whereas the factor of change for the global contrail cirrus radiative forcing in this scenario is reduced to 2.8. The decrease in contrail cirrus radiative forcing in this scenario is caused by the decrease in soot emissions. This means that radiative forcing due to contrail cirrus can be expected to increase faster in the future than that due to CO_2.

The increase in fuel efficiency included in the AEDT inventory does not conform with the CORSIA agreement unless a large part of the CO_2 emission reduction is reached by carbon offsetting. It is important to point out that carbon offsetting deals only with the impact of CO_2 emissions while leaving the impact of contrail cirrus on climate unchanged. Since the increase in contrail cirrus radiative forcing can be stronger than in CO_2 radiative forcing both radiative forcing components need to be considered in future agreements.

Contrail cirrus radiative forcing per flight distance appears to be particularly high in the tropics. This result should still be viewed with some caution, since in the tropical areas contrails form close to the threshold conditions which should lead to a lower contrail ice crystal nucleation rate (Kärcher et al., 2015). This has implications not only for contrail optical depth but also for the ice crystal loss rates during the vortex phase (Unterstrasser, 2016), microphysical process rates (Bier et al., 2017) and contrail cirrus life times (Burkhardt et al., 2018). When including a parameterization for contrail ice crystal nucleation this is likely to lead to a decrease in contrail cirrus radiative forcing in the tropics. The impact of the tropical areas on global contrail cirrus radiative forcing is still very limited so that the overestimation of contrail cirrus ice crystals has a limited impact on global contrail cirrus radiative forcing. As air traffic increases strongly in the tropical areas future simulations should include the impact of lower nucleation rates and the associated changes in ice crystal loss rates, changes in optical depth, microphysical process rates and contrail cirrus life time in the tropics.

Data availability. The data obtained from this study are available upon request from the authors.

Author contributions. L. Bock performed and analysed simulations. L. Bock and U. Burkhardt jointly discussed scientific results and wrote the paper.

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

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Simulation	background climate	inventory	air traffic volume [km a^{-1}]	propulsion efficiency	initial ice number concentration [cm-3]	coverage [%]	RF [mWm^{-2}]
C2006-T06	2006	2006	3.7 x~~*~~ 10^{10}	0.3	150	1.1 (0.7)	49 (56)
C2006-T50 ~~Plus~~	2006	2050 Baseline	15.4 x~~*~~ 10^{10}	0.3	150	2.9 (2.0)	159 (182*)
C2050-T50 ~~Baseline~~	2050 (RCP 6.0)	2050 Baseline	15.4 x~~*~~ 10^{10}	0.3	150	2.8 (2.0)	160 (183*)
C2050-T50M ~~Scenario 1~~	2050 (RCP 6.0)	2050 Scenario 1	15.4 x~~*~~ 10^{10}	0.42	75	2.8 (1.7)	137 (157*)

Table 1: Overview over the model simulations. Air traffic distance is given as ground projected track distance. Coverage is given for all contrail cirrus and in brackets for visible (visible optical depth > 0.05) contrail cirrus only (Bock and Burkhardt, 2016b). The radiative forcing is given for track distance and slant distance (see Sect. 2.2) in brackets. Asterisks mark extrapolated values calculated with the factor resulting from the radiative forcing in 2006 associated with air traffic volume using slant distance and track distance (Bock and Burkhardt, 2006b).

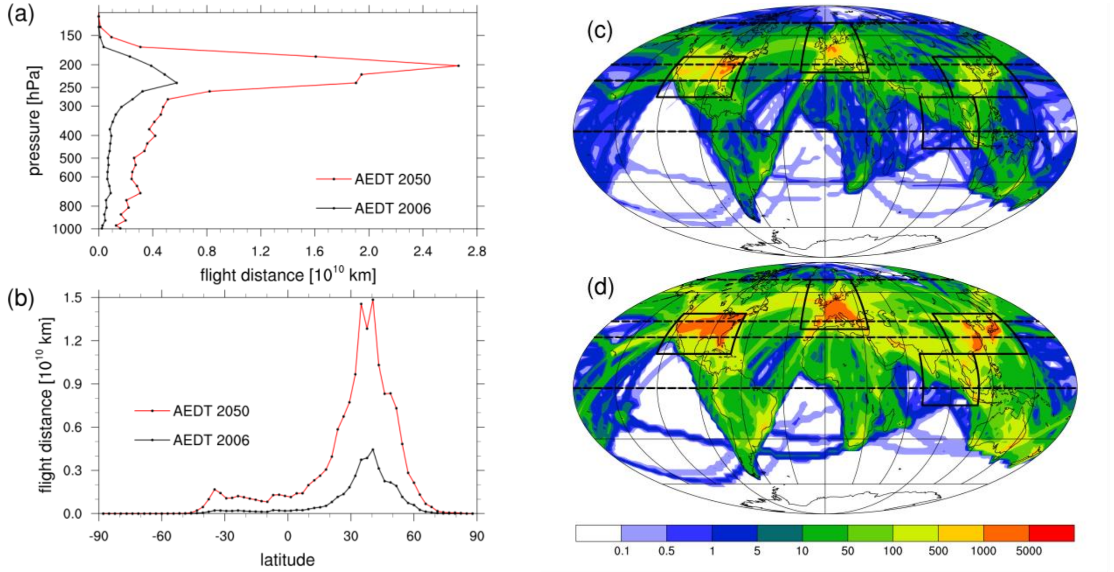

Figure 1: Vertical (a) and zonal (b) distribution of total annual flight distance and (c) horizontal distribution of vertically integrated air traffic density [km m^{-2} s^{-1}] for the years (c) 2006 and (d) 2050.

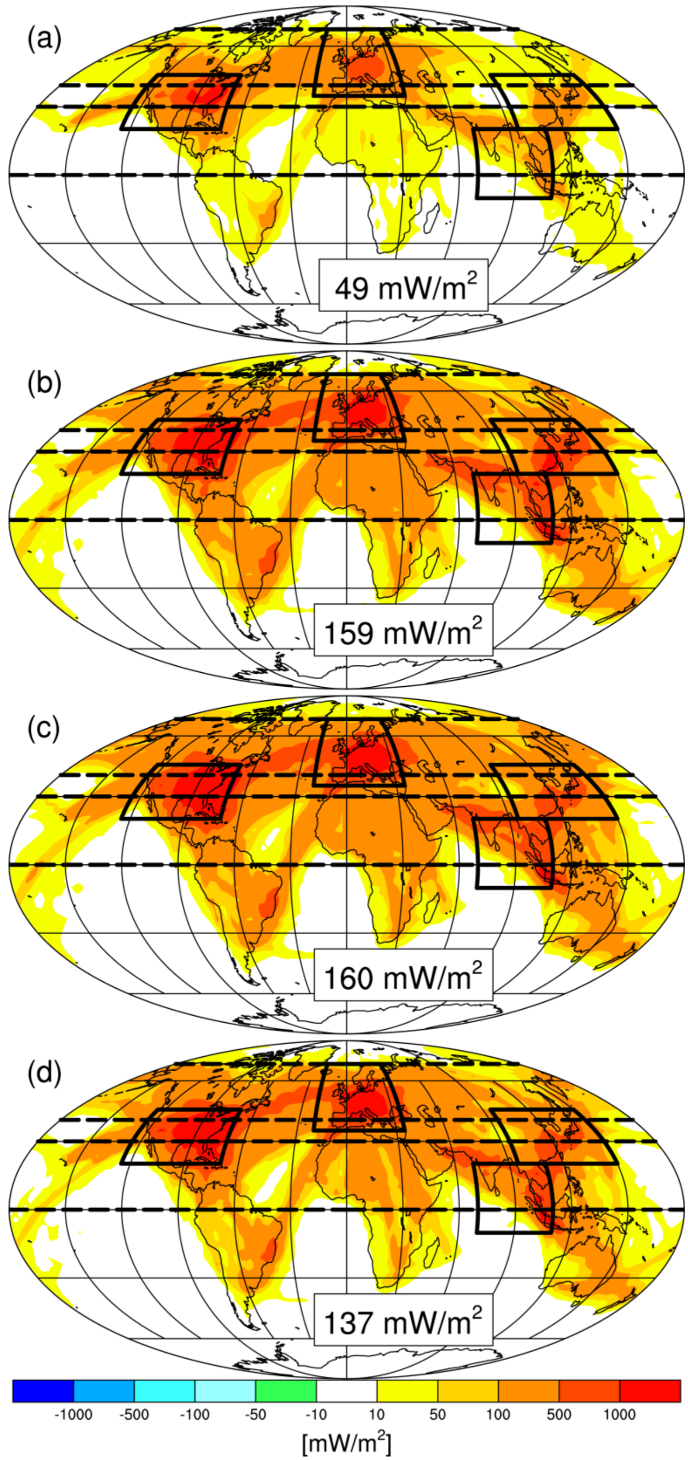

Figure 2: Radiative forcing in scenarios C2006-T06 (a), C2006-T50~~-Plus~~ (b), C2050-T50~~-Baseline~~ (c) and C2050-T50M~~-Scenario 1~~ (d). Boxes (solid lines) and latitude bands (dashed lines) indicate regions (defined in Sect 2.3) which we compare in Fig. 3 and 4.

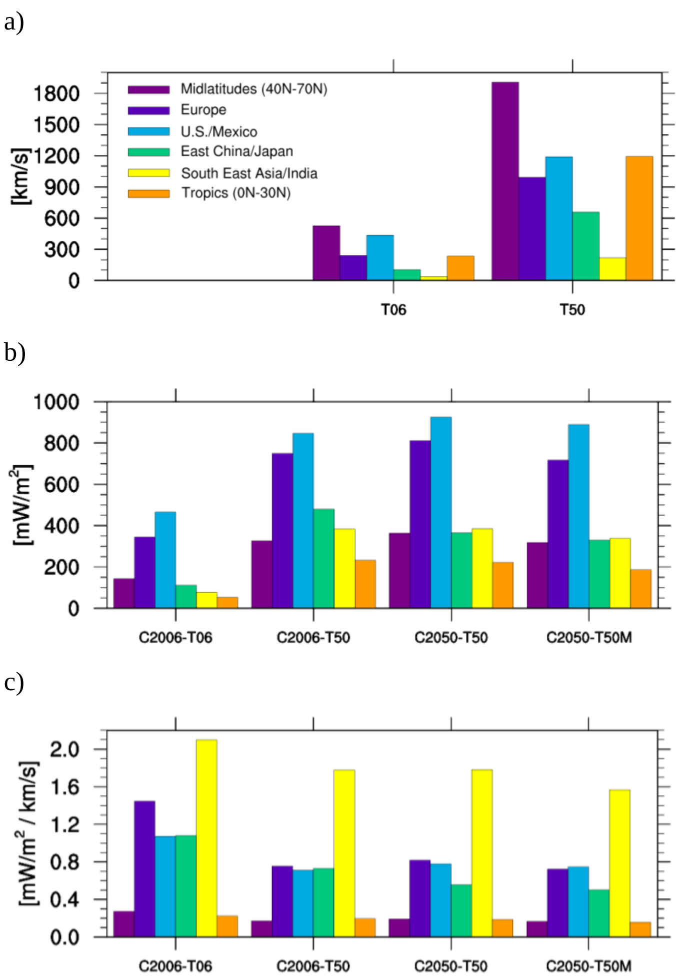

Figure 3: a) Flight distance [~~10^{10}~~ km/s] ~~per year~~ for 2006 and 2050 and b) contrail cirrus radiative forcing [mWm^{-2}] and c) contrail cirrus radiative forcing per flight distance for simulations summarized in Table 1 in different regions (same area size), in the mid-latitudes and in the tropics.

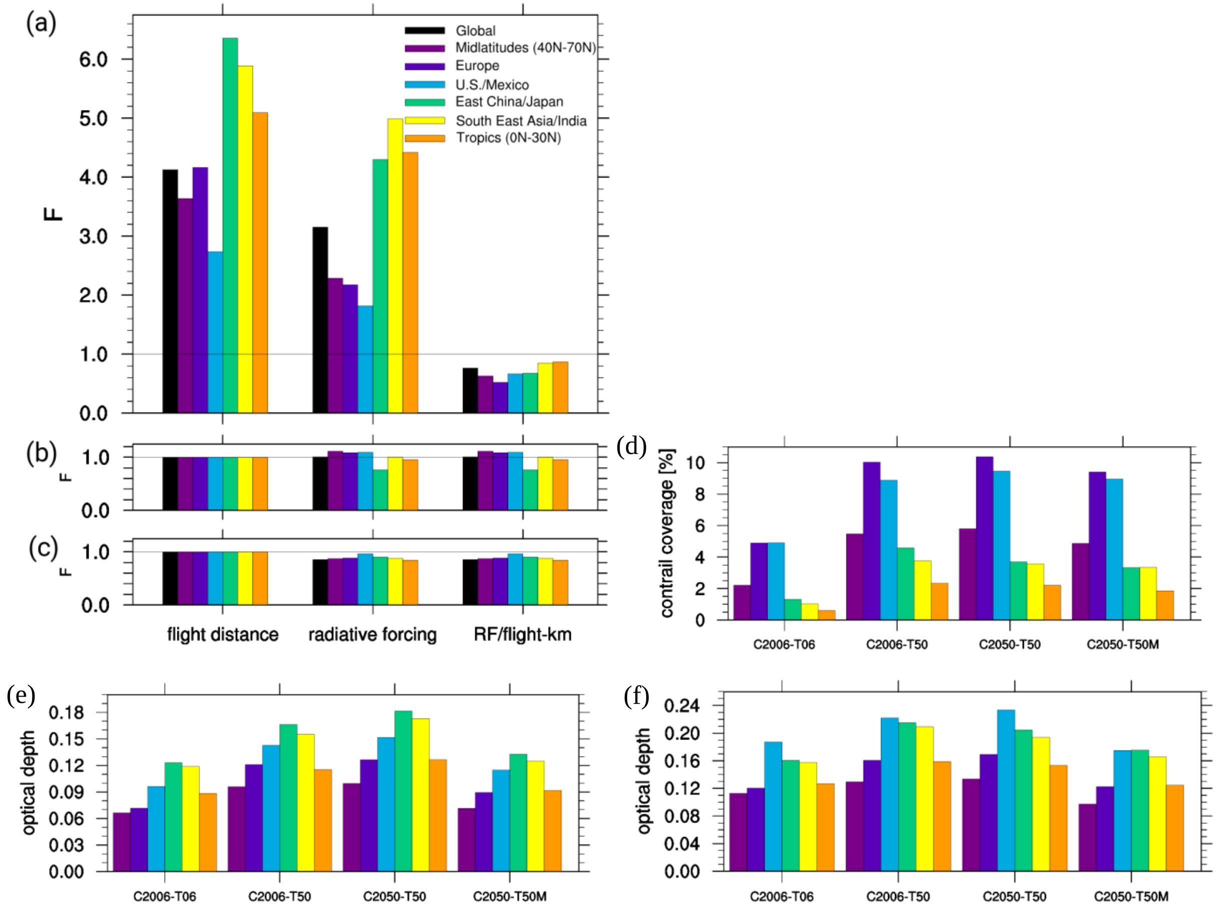

Figure 4: Factor of change (F) for flight distance, radiative forcing (RF) and ratio RF over flight distance from scenario C2006-T06 to C2006-T50~~P~~ (a), C2006-T50~~2006P~~ – C2050-T50~~ B~~ (b) and C2050-T50~~ B~~ to C2050-T50M~~ S1~~ (c). Also shown is the ~~Absolute change of (d) ~~mean contrail cirrus coverage (in %) due to contrail cirrus with an visible optical depth of >0.05 (d) and ~~(e) mean~~the mean visible optical depth at 200 hPa (e) and~~ (f)~~ 240 hPa (f) for different areas.

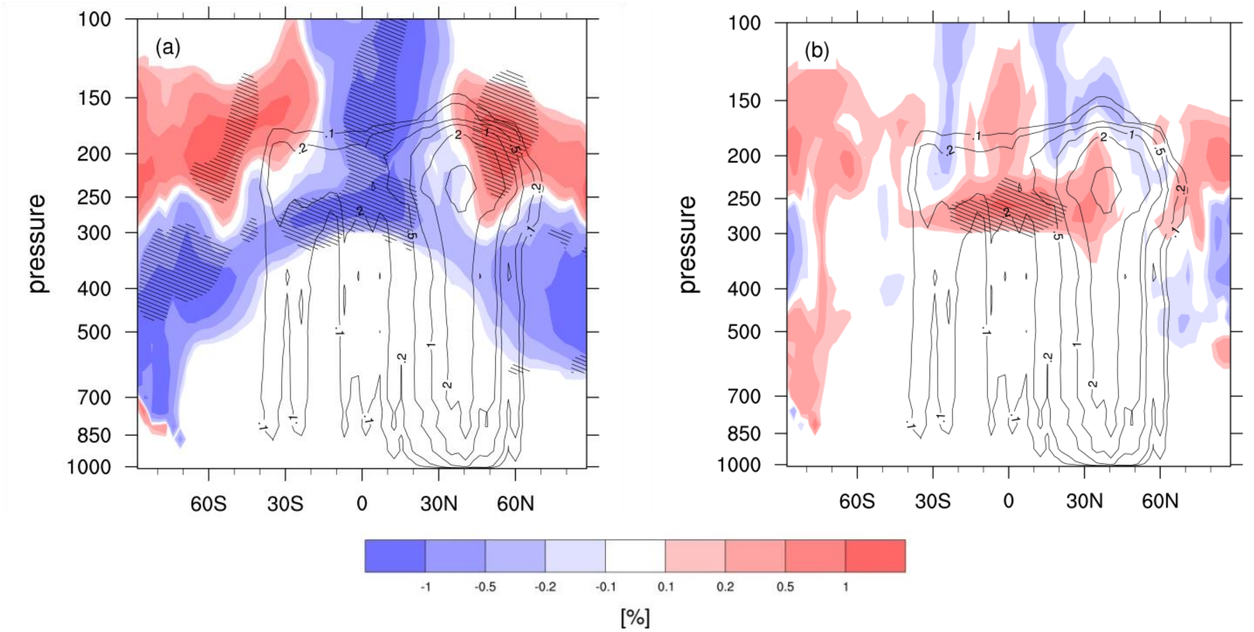

Figure 5: Changes in persistent contrail formation probability ~~frequency~~ from 2006 to 2050 due to climate change (a) and due to improved propulsion efficiency (b). Contour lines indicate annual flight distance [10^8 km] in 2050. ~~Dotted regions~~Hatched areas indicate statistically significant changes.

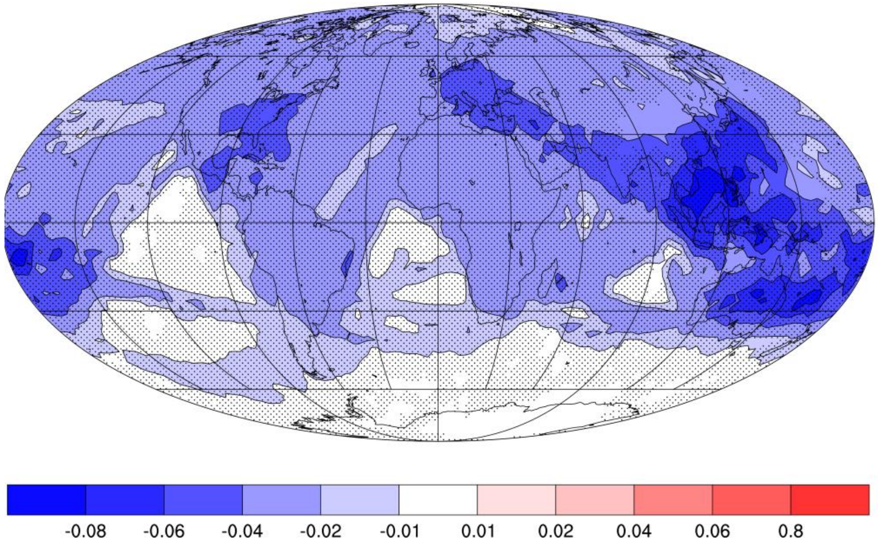

Figure 6: Absolute difference in visible optical depth in 200hPa between scenario C2050-T50 B and C2050-T50M S1 due to soot reductions. Dotted regions are significant.